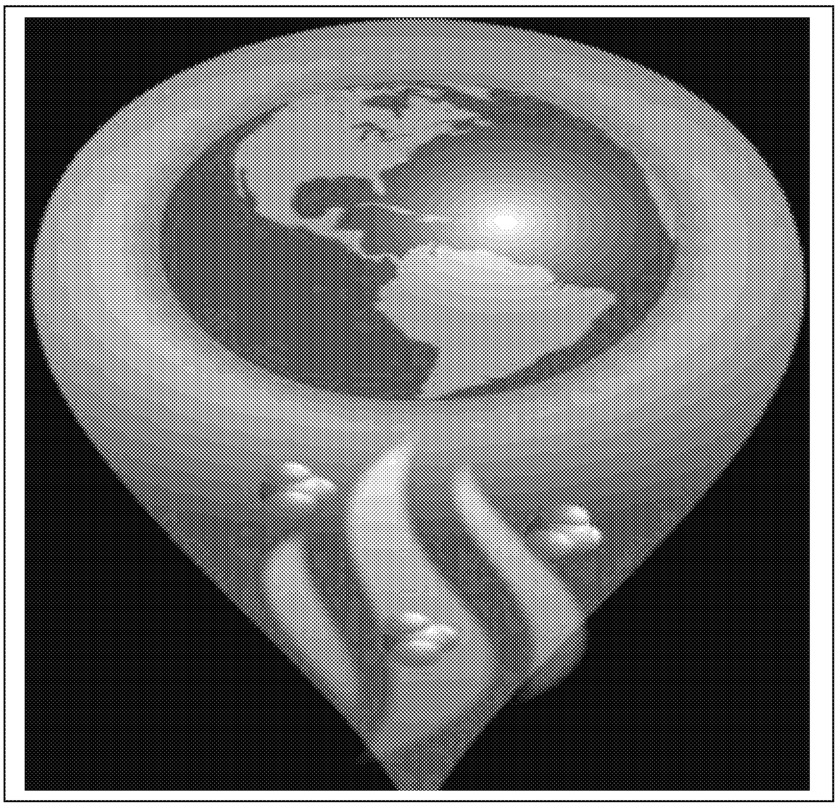
Technical/Regulatory Guidance

Draft
Evaluation of Innovative Methane Detection Technologies



External Draft
March 22, 2018

Prepared by
The Interstate Technology & Regulatory Council
Evaluation of Innovative Methane Detection Technologies Team
In Partnership with DOE-ARPA-E

ABOUT ITRC

The Interstate Technology and Regulatory Council (ITRC) is a public-private coalition working to reduce barriers to the use of innovative environmental technologies and approaches so that compliance costs are reduced and cleanup efficacy is maximized. ITRC produces documents and training that broaden and deepen technical knowledge and expedite quality regulatory decision making while protecting human health and the environment. With private and public sector members from all 50 states and the District of Columbia, ITRC truly provides a national perspective. More information on ITRC is available at www.itrcweb.org. ITRC is a program of the Environmental Research Institute of the States (ERIS), a 501(c)(3) organization incorporated in the District of Columbia and managed by the Environmental Council of the States (ECOS). ECOS is the national, nonprofit, nonpartisan association representing the state and territorial environmental commissioners. Its mission is to serve as a champion for states; to provide a clearinghouse of information for state environmental commissioners; to promote coordination in environmental management; and to articulate state positions on environmental issues to Congress, federal agencies, and the public.

DISCLAIMER

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Preliminary External Draft

March 22, 2018

Prepared by

The Interstate Technology & Regulatory Council

Evaluation of Innovative Methane Detection Technologies

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ACKNOWLEDGMENTS

The members of the Interstate Technology & Regulatory Council (ITRC) Evaluation of Innovative Methane Detection Technologies Team wish to acknowledge the individuals, organizations, and agencies that contributed to this technology and regulatory document.

As part of the broader ITRC effort, the Evaluation of Innovative Methane Detection Technologies effort is funded primarily by the U.S. Department of Energy.

The work team also wishes to recognize the efforts of the following individuals:

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EXECUTIVE SUMMARY

Substantial technological advances, particularly those affecting the production of oil and gas, have, over the past decade, significantly altered the "mix" of energy utilization in the United States and elsewhere in the developed world. Notably, power production in the United States has shifted away from oil-, coal-, and nuclear-powered electricity generation toward natural-gas powered generation; furthermore, the United States is on the verge of becoming a net exporter of natural gas. This shift presents both opportunities and challenges.

Several states have recently adopted or are considering regulations of methane emissions related to natural gas production and distribution. Moreover, the United States Environmental Protection Agency (EPA) and the Department of the Interior (DOI) have released proposed regulations for methane leaks at new sources and on Bureau of Land Management (BLM) lands. However, there is currently no standard methodology for state or federal lawmakers to evaluate equivalency or superiority of new methane detection technologies compared with those already approved. The purpose of this document is to provide an overview of existing and emerging methane detection technologies, as well as guidance regarding performance characteristics and parameters to consider in technology evaluation. It also endeavors to identify regulatory barriers to the use and adoption of new or innovative technologies that have the potential to reduce methane emissions. It is intended to enable regulators, facility owners and operators, and other users to evaluate, compare, and select suitable technologies that detect and quantify methane emissions from various segments of the oil and gas supply chain for compliance with existing and forthcoming methane emission (leak) regulations, monitor inventories, and enhance workforce and public safety.

Methane is the primary component in natural gas. The most significant segment in the oil and gas production and supply chain for methane emissions is natural gas field production (over 50%), followed by petroleum systems as a whole (over one-third), which in turn is followed by natural gas transmission and storage, natural gas processing, and natural gas distribution. State and Federal regulation of emissions is broken down according to these segments. At the Federal level, the EPA and BLM provide regulatory oversight for the production and processing segments of the oil and gas sector, whereas the Pipeline and Hazardous Materials Safety Administration (PHMSA) oversees transmission and distribution. The basis for these regulations varies from public health and environmental protection (EPA) to resource conservation (BLM) and safety (PHMSA). Delegated authority for these regulations is given to states to implement and is typically accomplished through a state's environmental or air quality department for production and processing and through the public utility commission (PUC) for transmission and distribution. States may also adopt their own regulations that are more strict than federal regulations.

There are currently only two main technologies for leak detection: EPA's Method 21 and optical gas imaging (OGI), with each offering advantages and disadvantages. Method 21 is an EPA established procedure used to detect VOC leaks from process equipment using a portable detecting instrument. The instrument detector shall respond to the compounds being processed and be capable of measuring the leak definition concentration specified in the applicable regulation (USEPA, 2017a). Detector types that may meet this requirement include, but are not limited to, catalytic oxidation, flame ionization, infrared absorption, and photoionization.

Commercial enterprises have also produced new detection techniques, such as the OGI cameras commercially offered by FLIR and by Opgal beginning in the early 2000's. These handheld cameras make detection possible by display in a screen, allowing visualization of a gas plume that is otherwise invisible to the naked eye.

Method 21 is based on easily enforceable concentration standards, but can be time- and labor-intensive, whereas OGI offers a quicker, more efficient approach and can be used to monitor hard-to-reach or unsafe equipment, but has a higher detection limit and lacks a written monitoring protocol.

The main objective for air quality related regulations is to reduce emissions to the maximum extent feasible while considering impacts such as cost, enforceability, and community concerns. In developing and amending regulations, regulators need significant levels of information on the technology or method being evaluated. Furthermore, regulations that include alternative compliance methods have the challenge of establishing equivalent compliance criteria for evaluating and approving a new method or technology.

Many technologies for methane detection exist in the market or are under development, evolving more rapidly in recent years. Performance criteria are needed to characterize these technologies according to their capabilities, limitations, costs, and uncertainties. The classification scheme presented in this document includes the following categories: primary data type (i.e., qualitative vs. quantitative); result type (e.g., yes/no vs. numerical value), which may be related to the deployment platform utilized; measurement temporal resolution (i.e., sampling rate); size; deployment method (e.g., walking, vehicle, fixed); specificity/speciation (i.e., methane only or also other hydrocarbons); working distance; environmental limitations (e.g., air temperature, wind speed or direction); calibration procedures; maturity; and others.

The methane detection technologies that are either currently available or under development fall into the following general categories:

- Forward Looking Infrared Camera (FLIR)
- Flame Ionization Detector (FID)
- Tunable Diode Laser
- High Flow Dilution Sampler
- Catalytic Combustion
- Metal Oxide
- Gas Chromatography (GC)
- Mass Spectrometry (MS)
- Printed Nanotubes

- Tunable Laser (Closed Path)
- Etalon
- Optical Gas Imaging (OGI)
- Fourier Transform Infrared (FTIR)

A technology user's goals, scale of application, accuracy and frequency of measurement, and the assumed distribution of methane emissions must be ascertained in order to select an appropriate technology. The following questions may be used to guide technology selection:

- What type of methane emissions are we trying to detect?
- How do the target emissions behave?
- What do we need to determine about the emission source?
- When and with what frequency do we want to inspect?
- At what scale are we applying the detection?

After defining the primary goal of a methane detection system, primary and secondary metrics must be developed, such as duration and location of a specific methane concentration, which in turn may depend on a sensor's detection limit and response time.

The concerns of stakeholders who may be asked to participate, or comment on specific technologies must be considered in this process The ITRC broadly defines "stakeholder" as members of environmental organizations, community advocacy groups, Tribal entities or other groups that deal with environmental issues, or a concerned individual who is not a member of any organization or group.

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1 INTRODUCTION

Recent years have seen significant changes in the U.S. energy economy, much of which has been driven by technological innovations such as horizontal drilling and hydraulic fracturing. Whereas the U.S. was previously dependent on imports of crude oil and natural gas from other countries, it is expected to become an exporter of liquefied natural gas (LNG) in the very near future. Furthermore, driven by concerns regarding environmental impacts linked to the burning of fossil fuels, there has been a shift in the U.S. to using cleaner-burning natural gas as a fuel for electricity generation and compressed natural gas for bus, truck, and automobile fleets. This change presents both opportunities and challenges. One of these challenges is how best to control methane gas emissions while embracing this new energy economy.

For example, natural gas poses a potential safety hazard to individuals and facilities along the entire production-to-consumption chain. From the perspective of producers and distributors, methane leaks represent a loss of product and thus revenue. Because methane is a potent greenhouse gas, it has led to a number of states developing regulatory mechanisms to detect and control methane gas emissions. Therefore, it is important to develop new and better technologies to detect methane emissions.

This document has been developed to assist state agencies tasked with developing regulations targeting emissions of methane from a variety of sources associated with the production, transmission, and distribution of natural gas by compiling information regarding a wide range of methane detection technologies, as well as developing a methodology for the evaluation of both current and future technologies for applicability to specific uses.

1.1 Purpose of Document

Several states have recently adopted or are considering regulations of methane emissions related to natural gas production and distribution. Moreover, EPA and DOI have released proposed regulations for methane leaks at new sources and on BLM lands. However, there is currently no standard methodology for state or federal lawmakers to evaluate equivalency or superiority of new methane detection technologies compared with those already approved. The purpose of this document is to provide an overview of existing and emerging technologies as well as guidance regarding performance characteristics and parameters to consider in technology evaluation. It also endeavors to identify regulatory barriers to the use and adoption of new or innovative technologies that have the potential to reduce methane emissions. This information is intended to enable regulators, facility owners and operators, and other users to evaluate, compare, and select suitable technologies that detect and quantify methane emissions from various segments of the oil and natural gas supply chain for compliance with existing and forthcoming methane emission (leak) regulations, monitor inventories, and enhance workforce and public safety.

1.2 Document Scope

- This document is focused primarily on the oil and gas industry because it has the most urgent need for methane detection technologies due to current regulatory requirements.

- Although the focus of this document is on methane detection technologies, there are regulations that apply to both methane and emissions of volatile organic compounds (VOCs), therefore the document also discusses VOCs in that context.

- This guidance addresses the regulatory environment pertaining to on-shore methane emission sources. Although off-shore emissions are of equal concern, these facilities are difficult to access (e.g., production platforms) and may be located in marine or sub-marine environments (e.g., platform-to-shore pipelines), and thus may require a different approach to methane emission detection

- This document encompasses existing and developing detection technologies, but does not delve into on-going R&D efforts; the detection technology field is dynamic and rapidly-evolving, and this guidance may require significant updating in a relatively short period of time

- This document is intended to provide a reasonably comprehensive overview of available methane detection technologies, but not an exhaustive compilation of all technology combinations (e.g., same sensor on different mobile platforms).

- Similarly, this guidance is intended to provide an overview of the current regulatory environment, but does not seek to serve as an exhaustive, all-inclusive reference for methane emissions regulations in all 50 states and on federal lands.

Although this guidance document is focused on addressing the needs of the oil and gas industry, it may also provide useful information for other industries that have a need to detect or monitor methane emissions.

1.3 Intended Audience

This document is intended for wide audience and may be used as follows:

- Regulatory, technical staff and managers from local government authorities, state environmental programs, and from Federal environmental, land management and energy programs can use this guidance for the following:

    - To inform their decisions regarding the requirements incorporated into pending or future regulations

    - To revise existing regulations to allow for application of new technologies or existing technologies in new ways or to declare equivalence between new and existing technologies

    - As a general reference

- Technology developers and vendors can use this document to inform their research and development efforts

- Oil and gas producers, transmission companies, distribution utilities, municipalities, and large facilities with interest in detecting and managing methane releases can use this guidance to assist in selecting existing or emerging methane detection technologies to address the requirements of existing or pending regulations and as a general reference.

Other audiences may include academics involved in researching, developing or evaluating methane-detection technologies, as well as tribal, environmental, community and other interested stakeholders. This guidance will provide them with a common understanding of available and emerging methane detection technologies, a methodology for assessing the applicability of a given technology for a particular purpose or environment, and of regulator expectations for technology performance.

1.4 Framing the Guidance Document

This section will clarify the perspectives of various end users were evaluated in this document.

1.4.1 State Survey for Regulations

A survey of states was made using the ITRC's State Point of Contacts (POC) to collect information on laws, policies, and regulations requiring Leak Detection and Repair (LDAR) or control of methane emissions from the oil and natural gas industries. Thirty-six state POCs responded and of those fourteen reported having relevant regulations in place or under consideration, with six of those requiring both LDAR and control of methane emissions. This survey is discussed in greater detail in the Appendix C – Additional Regulations Material [link]. Most existing regulations rely on EPA Method 21 for leak detection with a few states also allowing the use of optical gas imaging (OGI) cameras.

1.4.2 Industry Perspective and Concerns

Substantial industry, government, and private funding has spurred the development of many methane detection products and services. From an industry perspective, there are several features that must be considered for technology selection in the methane detection space. First, methane detection strategies need to be applicable for the industry segment for which they are intended. For example, vehicle-based platforms that could be deployed to monitor dense, urban natural gas distribution systems are unlikely to be the ideal solution for monitoring geographical dispersed oil and gas production sites. Second, cost effectiveness targets must account for the method under which the industry segment actually recovers cost. For example, the production segment tends to assess leak detection and repair costs in relationship to recovered gas while natural gas distributors tend to be assigned defined budgets for repair activities based on collections from local rate payers. Finally, technologies that would like to be considered for large scale deployment must be pilot tested in field locations over an extended period while including advanced analytics to sort out actual detections from measurement noise in order to yield actionable insights.

Furthermore, it is important that regulations are flexible enough to incorporate innovative technological solutions even if the performance of the technologies is not identical to those on which the regulation was originally based. For example, several states have adopted regulations that require periodic surveys of oil and gas infrastructure with handheld OGI cameras to locate emission sources. In theory, a technology solution, such as a satellite or an inexpensive wellpad sensor, could be used to identify larger sources more quickly than periodic manned surveys, and this could result in the better emission reductions despite having higher (poorer) detection thresholds.

1.4.3 Tribal, Environmental, and Community Stakeholder Concerns

The ITRC broadly defines "stakeholder" as members of environmental organizations, community advocacy groups, Tribal entities or other groups that deal with environmental issues, or a concerned individual who is not a member of any organization or group. Public stakeholders, such as advocacy groups, often speak for the communities that are affected by environmental issues. In this document, a differentiation is made between public stakeholders and interested parties (oil and gas companies, pipeline operators and state regulators.)

ITRC has found that environmental regulators and other parties benefit from informed, constructive stakeholder involvement because it can help them to make better decisions, and reduce the likelihood of costly, time-consuming repeated work. It also allows those in affected communities to participate in decisions regarding the long-term use of land, water, and other resources.

Stakeholders recognize that there are limitations to the areas addressed in this document. The purpose of this document is to provide an overview of existing and developing technologies as well as guidance regarding performance characteristics and parameters to consider in technology evaluation. However, it does not provide an exhaustive, all-inclusive reference for methane emissions in all sectors, in all states, from all sources.

There may still be stakeholder concerns not accounted for in this document. Accordingly, representatives of interested parties who are coordinating discussions of evaluation methodologies or specific technologies with regards to methane detection should be aware that stakeholders may have additional concerns such as those discussed in [HYPERLINK \l "_Lessons_Learned"].

Specific concerns about emissions include safety due to the explosive and flammable properties of natural gas, and the air quality implications, as methane and natural gas co-pollutants are either toxic, carcinogenic, or contribute to regional particulate matter and ozone formation. Methane is also a potent greenhouse gas responsible for 25% of the additional heat trapped by the atmosphere due to human activities (Etminan, 2016).

1.5 Document Content

This document is arranged into the following sections:

- Section 2 – Characterization: identifies all the known sources of fugitive methane emissions within the oil and gas sector and characterizes the types of emissions and rates that may be expected from each of these sources. Regulatory barriers to the use of various types of methane detection technologies will also be addressed such as various types of overly-restrictive language.

- Section 3 - Regulations: summarizes existing and proposed laws and regulations of local, state, and federal governments that focus on methane leak detection and repair programs for the oil and gas sector. The current needs of existing laws and regulation are also defined, as well as any constraints on the use of technology, legal or otherwise. Regulations in Canada, Europe and other countries are also briefly addressed.

- Section 4 – Technology: discusses the relevant available methane detection technologies and their functional attributes, including whether the data captured is qualitative or quantitative. The type of data is provided as well as whether the measurements are instantaneous or continuous; the relative size of the instrument; the instrument's working distance and how it may be deployed. Lastly, the relative costs and other relevant attributes are noted.

- Section 5 – Evaluation: provides a framework for the evaluation of methane detection technologies, including metrics and procedures for assessing primary and secondary data quality. This section also provides a framework for technology equivalence determination.

- Section 6 – Lessons Learned: identifies and discusses the lessons that have been learned in the generation of this document.

- Section 7 – Stakeholder Concerns: addresses the concerns of stakeholders who may be asked to participate, or comment on evaluation methodologies or specific technologies with regards to methane detection. Stakeholders recognize that the purpose of this document is to provide an overview of existing and developing technologies as well as guidance regarding performance characteristics and parameters to consider in technology evaluation. It is often important to explain how methane contributes to environmental degradation (e.g., climate change) and safety in a reasonable, scientific way, and what can be done to reduce its impacts.

Appendices are included at the end of the document to present additional information as follows:

- Appendix A: Case Studies Summarized
- Appendix B: Additional Characterization Section Materials
- Appendix C: Additional Regulations Section Materials
- Appendix D: Team Contacts
- Appendix E. Glossary
- Appendix F. Acronyms

2 CHARACTERIZATION OF EMISSIONS

2.1 Introduction

Methane is a component of emissions from a variety of sources all along the natural gas and petroleum systems. Along with methane the system typically contains other components like volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) like benzene. Moving downstream from wells to natural gas end users the VOC and HAPs generally decrease, while methane fraction increases to about 95%. The EPA tracks methane emissions from the natural gas and petroleum systems in their annual Greenhouse Gas Inventory (USEPA, 2017a) and oil and gas companies report their methane and carbon dioxide emissions through the [HYPERLINK "https://www.epa.gov/ghgreporting/subpart-w-petroleum-and-natural-gas-systems"]. EPA estimates that natural gas and petroleum systems account for 31% of anthropogenic methane emissions in the U.S (USEPA, 2017a). In this chapter we introduce the reader to the natural gas and petroleum system supply chain and we briefly describe the various sources of methane. Further details and emission data is provided in the Appendices [insert link].

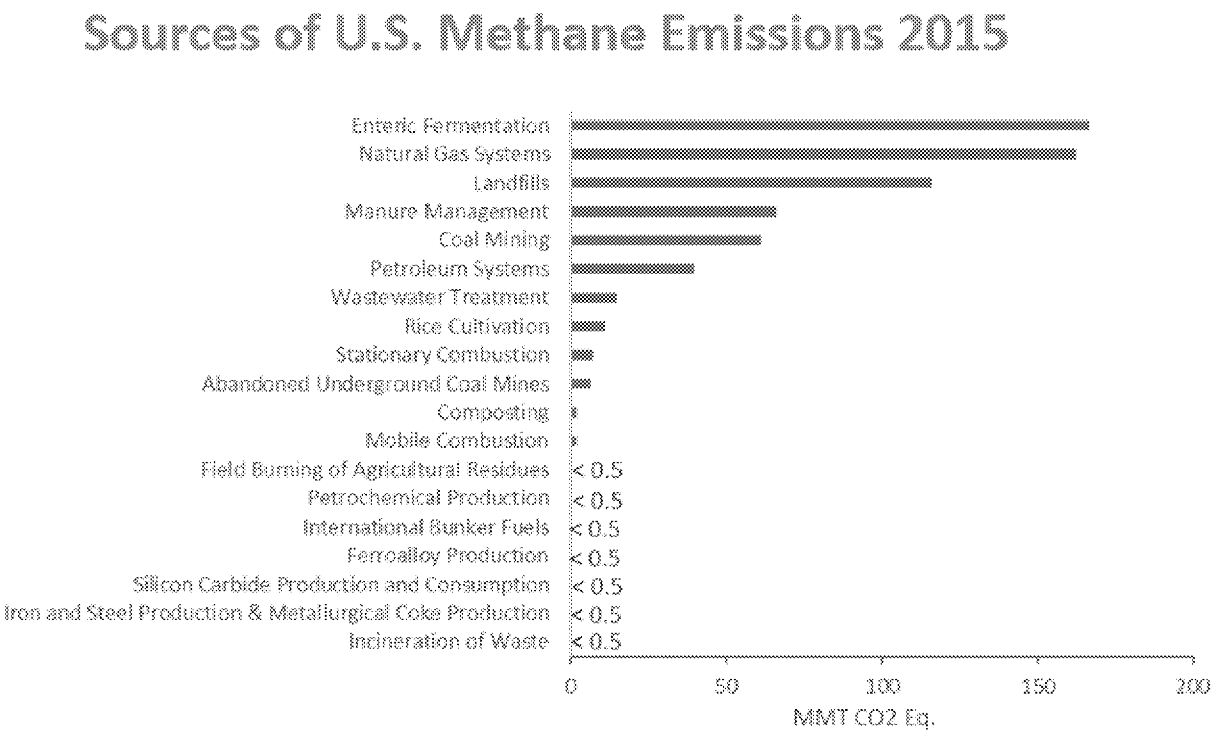
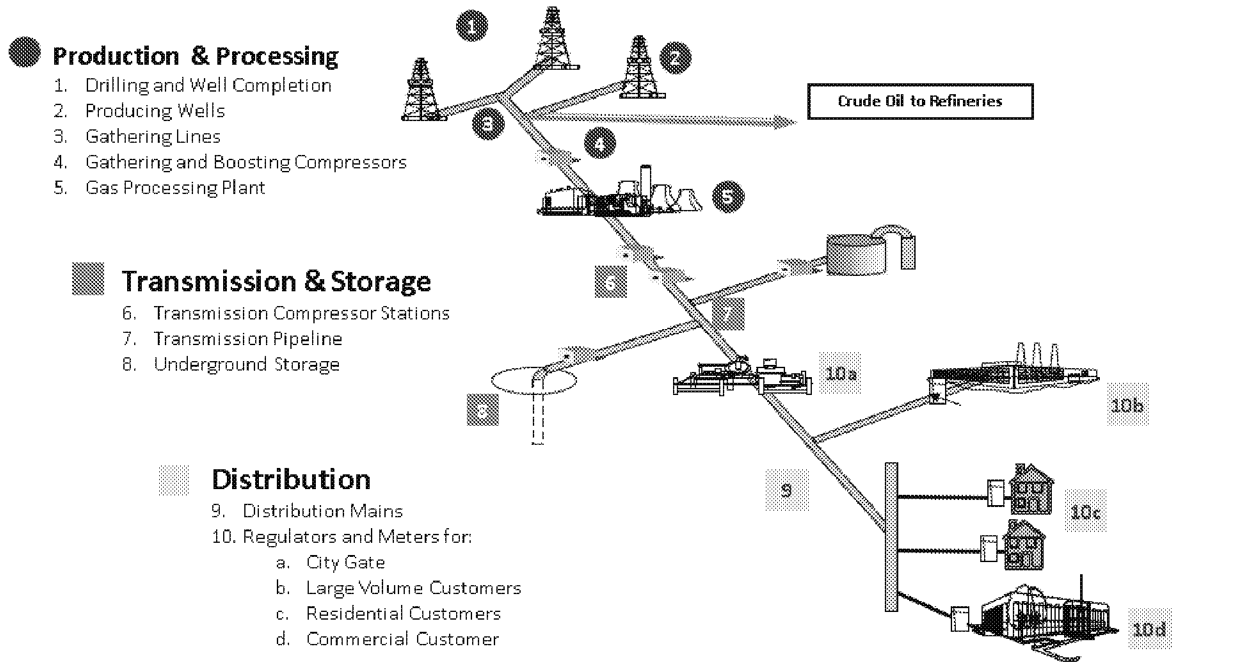


Figure [SEQ Figure * ARABIC]. USEPA Greenhouse Gas Inventory Reporting Year 2015 - Natural Gas and Petroleum Systems Annex 3

Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2015, Environmental Protection Agency (April 2017). Courtesy of the American Gas Association

The schematic below is used in EPA and other industry sources to orient the reader to the natural gas and petroleum system supply chain. This document will generally follow this supply chain.



Source: Adapted from American Gas Association and EPA Natural Gas STAR Program

Figure [SEQ Figure * ARABIC]. Schematic of the natural gas and petroleum system supply chain

Nomenclature used to describe the supply chain in natural gas and petroleum systems varies so first we will describe the organization provided in this chapter as compared to the US EPA Greenhouse Gas Inventory and the US EPA Greenhouse Reporting Program – subpart W. Tables 1 and 2 below show where each process falls into each of the systems of organization.

Table [SEQ Table * ARABIC]. Comparison of natural gas system characterization of Subpart W, GHG Inventory and this assessment

Source (GHG Inventory)	Natural Gas Systems (Annex 3.6)										
Stage (GHG Inventory)	Field Production					Processing	Transmission & Storage			Distribution	
Natural Gas Supply Chain	Drilling	Well Completion	Producing Wells	Gathering Lines	Gathering & Boosting Stations	Gas Processing Plant	Transmission Compressor Stations	Transmission Pipeline	Underground Storage	Distribution Mains/Services	Regulators & Meters
Segment (GHGRP-Subpart W)	Onshore Production			Onshore Gathering & Boosting		Onshore Natural Gas Processing	Onshore Transmission Compression	Onshore Natural Gas Transmission Pipeline	Underground Natural Gas Storage	Distribution	

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Table [SEQ Table * ARABIC]. Comparison of petroleum system characterization of Subpart W, GHG Inventory and this assessment

Source (GHG Inventory)	Petroleum Systems (Annex 3.5)					
Stage (GHG Inventory)	Production Field Operations				Crude Oil Transportation	Refining
Petroleum Supply Chain	Drilling	Well Completion	Producing Wells	Gathering Lines	Crude Oil to Refineries (not addressed here)	
Segment (GHGRP-Subpart W)	Onshore Production			Onshore Gathering & Boosting		

The quantity of emissions and composition of those emissions can vary significantly between each of the supply chain segments and even within the same segment. The key factors that affect the amount of emissions from a given operation are the availability of infrastructure, how well-maintained the system is, the amount of waste gas created, and the incentives or regulatory requirements to control waste-gas volumes or to reduce fugitive emissions.

The composition of the gases emitted to the atmosphere through the natural gas and petroleum supply chains varies by field from the geophysical and geochemical reservoir conditions in the production segment, by equipment sources within a segment (processing/treatment requirements, design and operating practices), and by segments successively downstream as the gas stream is processed and impurities removed.

Typically, production and processing activities tend to have greater amounts of fugitive emissions as a percentage of throughput than downstream activities (Intergovernmental Panel on Climate Change, 2006).

Within the production segment emission composition varies by the particular process within the segment. For example, the gas supply for pneumatic devices is from the separator gas and so it has a higher percent methane and a lower percent of VOCs than the gaseous emissions from liquid hydrocarbon storage tanks. Even the emission composition from hydrocarbon storage tanks varies considerably dependent on, among other process parameters, the composition of the pressurized liquid entering the tank. If there was a stuck open dump valve that unintentionally carried through gas from the separator, the emission stream from the storage tank would be higher in methane than routine flashing and working/standing/breathing emissions.

Transmission pipeline gas quality is mostly methane, since end-use processes and equipment require furl for safe and reliable operation ~~designed to ensure that gas is safe and reliable, and meets the requirements of end-use applications in the distribution segment and so is mostly methane~~. See the Appendix B for more details [insert link].

Some of these emission sources may be regulated and others not. For example, some but not all states have regulations requiring emission reductions from storage tanks depending upon the potential emissions from that equipment. States could have differing thresholds where emission reductions would be required. A federal regulation also covers storage tanks constructed since August 2011 that emit over six tons per year of volatile organic compounds. See the [HYPERLINK \l "_Regulations"] [insert link] for more details.

~~Typically, production and processing activities tend to have greater amounts of fugitive emissions as a percentage of throughput than downstream activities (Intergovernmental Panel on Climate Change, 2006).~~

The sources of fugitive emissions on oil and gas systems include, but are not limited to, equipment leaks, evaporation and flashing losses, venting, flaring, incineration and accidental releases. While some of these emission sources are engineered or intentional, and therefore relatively well characterized, the quantity and composition of the emissions is generally subject to significant uncertainty (IPCC, 2006). For further complexity, some of these emission sources are continuous and some are intermittent.

Examples of intentional engineered emission releases[x] [insert link to discussion in Appendix] include:

- Venting or flaring of continuous process waste streams (e.g. tank emissions, glycol dehydrator regenerator emissions)
- Storage Losses (Flashing, working and breathing losses)
- Fuel combustion
- Incinerators
- Equipment depressurization and blowdown for maintenance
- Use of natural gas as the supply medium for pneumatic devices

Examples of unintentional engineered emission releases[x] [insert link] include:

- Emergency pressure relief
- Fugitive equipment leaks
- Leakage into vent and flare systems
- Emissions from engine crankcase vents
- Venting and flaring due to power outages and process upsets

Examples of non-engineered emission releases include:

- Unintentional gas carry-through to storage tanks (e.g. leakage past the seats of drain and dump valves, malfunctioning level controllers, set-point of the liquid-level controller on a separator or scrubber is too low, inefficient upstream gas/liquid separation)
- Venting from blowdown vents (when maintenance is *not* occurring due to leaking valve)
- Spills and accidental releases (e.g. well blowouts, pipeline breaks, tank explosions, gas migration to the surface around the outside of wells, and surface-casing vent blows)

- Incomplete combustion, unburned hydrocarbons (beyond that which is anticipated in design) (engines, heaters, heat exchangers, flares, combustors)
    - Deteriorated performance due to wear or malfunctioning of components (e.g. leakage past pistons in engines)
    - Inefficient loading (e.g. oversized engines, poor air-fuel ratio tuning)
    - Fouling problems
    - Use of old or outdated technologies
    - Abnormal process or improperly operated
- Operator error (e.g. manual drain valve left partially open)
- Gas migration to the surface around the outside of the well casing
- Underground pipeline leaks
- Surface casing vent blows
- Improperly sized, maintained or functioning emission control systems
    - Vapor collection systems
    - Catalytic converters
    - Flame failures

The very breadth of processes required for the natural gas and oil supply chain demonstrates the need for varied leak detection technologies. Sources of leaks contain different compositions, frequencies and flowrates requiring the selection of appropriate leak detection technology.

3 REGULATIONS

3.1 Objectives & Introduction

This section provides an overview of present existing and proposed laws and regulations on methane emissions dealing with leak detection from the oil and natural gas supply chain. Additional detail on these regulations at the local, state, federal and international level can be found in Appendix C [insert link]. These regulations can be placed under the general umbrella term of "Leak Detection and Repair (LDAR)" requirements. Some of these regulations concurrently regulate volatile organic compounds (VOCs) with methane in the fugitive emissions or gas stream.

Methane is considered a greenhouse gas (GHG) while VOCs contribute to the formation of ground-level ozone, which is a criteria air pollutant under the United States Federal Clean Air Act. Some VOCs are also toxic to human health, such as benzene. This section will differentiate between oil and gas fugitive emission or LDAR regulations that apply to methane only, VOCs only, and methane plus VOCs. Note that regulations that only apply to VOCs have the co-benefit of reducing methane emissions as well since all emissions in the gas stream are addressed through LDAR activities.

In addition, this section identifies regulatory barriers and constraints on the approval, use and adoption of new or innovative fugitive emission detection technologies, including those specific to methane, and identifies regulatory concerns and considerations in this regard, as well as areas of opportunity.

Regulation of fugitive emissions from the oil and gas sector, particularly in the United States, is broken down by the various segments of the sector from drilling and production through transmission and distribution (see the Characterization section for more details on the oil and gas sector segments and emission sources in those segments). Tables 3 and 4 summarize these regulations by segment and regulator (local, state, federal and international government). United States federal regulatory agencies that oversee fugitive emissions or equipment leaks from the oil and gas sector include the Environmental Protection Agency (EPA), Bureau of Land Management (BLM), which is part of the Department of Interior, and the Pipeline and Hazardous Materials Safety Administration (PHMSA), which is part of the Department of Transportation. The EPA and BLM provide federal regulatory oversight for the production and processing segments of the sector, while PHMSA oversees transmission and distribution (pipelines). The basis for these regulations vary from public health and environmental protection (EPA) to resource conservation (BLM) and safety (PHMSA).

State that have been delegated regulatory authority from EPA and PHMSA, typically implement applicable regulations through a state's environmental department and public utility commission (PUC) or other similar agency. However, states can also adopt their own regulations that may exceed federal requirements, such as California, Colorado, Ohio, and Pennsylvania. A number of these states have specifically targeted methane as part of their regulations, with a focus primarily on the production, processing and storage segments of the oil and gas sector. It should be noted that state regulations cannot be less stringent than federal regulations. For this reason, most states adopt federal regulations.

A state agency participating in PHMSA's pipeline safety program is required to adopt federal pipeline safety regulations. In addition, a state agency may issue additional or more stringent standards concerning intrastate pipelines as long as they are compatible with federal regulations. States may also specifically target methane in addition to safety in this segment.

Local governments can also adopt their own fugitive emissions regulations and/or have delegated authority to implement federal or state requirements. For example, in California local air quality management districts implement federal and state rules, in addition to local VOC LDAR regulations, helping to meet national ambient air quality standards.

Table 3 summarizes existing and proposed oil and gas fugitive emission regulations by federal, state, local and international governments with information on prescribed monitoring methods and technologies, including allowance of approved alternative technologies or methods, pollutant regulated (methane, VOCs), instrument-based monitoring frequency, leak standards or definitions, and affected facilities. A more detailed summary of specific fugitive emission regulations that target or include methane and/or allow use of approved alternative leak detection technologies is provided in Appendix C [insert link]. Please refer to the Executive Summary of this document for definitions of Optical Gas Imaging (OGI) and EPA Method 21.

Table 4 summarizes applicable fugitive emission/leak detection regulations (existing and pending) by segment in the oil and natural gas supply chain. Please refer to the Characterization section of this document for details on the oil and natural gas supply chain segments.

Table [SEQ Table * ARABIC]. LDAR Regulations by Government

Government Type (Federal, State, Local, International), Agency & Rule	Required Monitoring Method or Technology	Alternative Monitoring Method or Technology Allowance	Pollutant Regulated	Instrument-Based Monitoring Frequency	Leak Standard (ppm = parts per million)	Affected Facilities
Federal, EPA, NSPS OOOOa	Optical Gas Imaging (OGI), Method 21 (M21)	Yes	Methane + VOC	Quarterly (compressor stations); semi-annual (well pads)	500 ppm (M21); any detectable emissions (OGI)	New and modified production facilities & gas processing plants*
Federal, EPA, NSPS OOOO	Method 21	Yes (OGI only – Alternative Work Practice)	VOC	Varies	Varies	Gas processing plants
Federal, PHMSA, 49 CFR Part 192	Varies	Yes	Methane	Varies based on location (at least every 5 years)	Varies based on location	Natural gas pipeline systems
Federal, BLM, 43 CFR Parts 3100, 3160 and 3170	Optical Gas Imaging (OGI), Method 21 (M21)	Yes	Methane	Quarterly (compressor stations); semi-annual (well pads)	500 ppm (M21); any detectable emissions (OGI)	New and existing production facilities
Canada, Federal, (PROPOSED)	Optical Gas Imaging (OGI), Method 21	Yes	Methane + VOC	3 times per year	500 ppm (M21); any detectable emissions	New and existing production processing,

Government Type (Federal, State, Local, International), Agency & Rule	Required Monitoring Method or Technology	Alternative Monitoring Method or Technology Allowance	Pollutant Regulated	Instrument-Based Monitoring Frequency	Leak Standard (ppm = parts per million)	Affected Facilities
	(M21)				(OGI)	transmission and storage facilities.
Canada, Provincial, Alberta – Directive 084	Optical Gas Imaging (OGI), Method 21 (M21)	Yes	Methane + VOC	Monthly	500 ppm (M21); any detectable emissions (OGI)	Peace River area only. Existing facilities associated with heavy oil and bitumen operations
State, California, Air Resources Board (CARB)	Method 21	No	Methane	Quarterly	1,000 ppm	New and existing production processing, transmission and storage facilities.
State, California, Air Resources Board (CARB)	Method 21 (M21), Optical Gas Imaging (OGI) or other CARB approved method	Yes	Methane	Daily/Continuous	Any detectable	Underground Gas Storage Facilities & Wells
State, California, Public Utilities Commission (CPUC)	Optical Gas Imaging (OGI), Method 21 (M21) or other methods	Yes	Methane	Every 3 Calendar Years or alternative frequency that demonstrates comparable or better performance.	Develop leak size action threshold methodology with CPUC & CARB; "Find-and-Fix" until then (any detected leaks)	Gas Transmission, Distribution and Storage Facilities & Pipelines
State, California, Division of Oil, Gas & Geothermal Resources *(EMERGENCY REGULATIONS) *Note: moves to CARB provisions once storage monitoring plans*	Optical Gas Imaging (OGI) or other effective gas leak detection technology	Yes	Methane	Daily	Not specified	Underground Gas Storage Projects & Wells

Government Type (Federal, State, Local, International), Agency & Rule	Required Monitoring Method or Technology	Alternative Monitoring Method or Technology Allowance	Pollutant Regulated	Instrument-Based Monitoring Frequency	Leak Standard (ppm = parts per million)	Affected Facilities
finalized						
State, California, Division of Oil, Gas & Geothermal Resources *(PROPOSED)*	An Accepted Industry or Regulatory Standard	See Required Monitoring Method or Technology	Methane	Annual	Not specified	Gas Pipelines in Sensitive Areas
State, Colorado, Air Quality Control Commission – Regulation No. 7	Optical Gas Imaging (OGI), Method 21 (M21)	Yes	Methane + VOC	Monthly, Quarterly and Annual	500 ppm, 2,000 ppm (M21); any detectable emissions (OGI)	New and existing production facilities
State, Colorado, Oil & Gas Conservation Commission *(PROPOSED)*	Audio/Visual/ Olfactory (AVO), Optical Gas Imaging (OGI), LASERs, or other detection technology	Yes	Methane + VOC	Not Specified	Grade 1 Gas Leak	Oil & Gas Flowlines at/from Well Production Facilities
State, Pennsylvania, Dept. of Environmental Protection	Optical Gas Imaging (OGI), Method 21	Yes	Methane + VOC	Quarterly for Natural Gas Compression and Processing facilities. Annually for Natural Gas Transmission facilities and Natural Gas Well sites.	Any release of gaseous hydrocarbons	Any production facility covered by GP-5 or PE #38
State, Pennsylvania, Dept. of Environmental Protection *(PROPOSED)*	Optical Gas Imaging (OGI), Method 21	Yes	Methane + VOC	Quarterly for Natural Gas Compression and Processing facilities and Natural Gas Well sites (frequency reduced to semi-annually if the percentage of	Any release of gaseous hydrocarbons	Any production facility covered by GP-5, GP-5A or PE #38

Government Type (Federal, State, Local, International), Agency & Rule	Required Monitoring Method or Technology	Alternative Monitoring Method or Technology Allowance	Pollutant Regulated	Instrument-Based Monitoring Frequency	Leak Standard (ppm = parts per million)	Affected Facilities
				leaking components is less than 2%).		
State, Ohio, Environmental Protection Agency	Optical Gas Imaging (OGI), Method 21 (M21)	Yes	Methane + VOC	Quarterly, then Varies	500 ppm, 10,000 ppm (M21); any detectable emissions (OGI)	Any production facility covered by GPs 12.1, 12.2 and 18.1
State, Utah, Dept. of Environmental Quality	Optical Gas Imaging (OGI), Method 21 (M21), TDLAS ("laser")	No	VOC	Quarterly and Annual	500 ppm (M21, TDLAS); any detectable emissions (OGI)	New and existing production facilities
State, Utah, Dept. of Environmental Quality *(PROPOSED)*	Optical Gas Imaging (OGI), Method 21 (M21)	No	VOC	Semi-Annually; Annually for difficult to monitor components	Any detectable emissions	Well production facilities
State, Wyoming, Dept. of Environmental Quality	Optical Gas Imaging (OGI), Method 21 (M21)	Yes	VOC	Quarterly	Any detectable emissions (OGI); M21 leak threshold not specified (review & approval of threshold request by WY DEQ)	Production facilities in existence prior to 1/1/14 in ozone non-attainment area
Local, California, Various Air Districts	Method 21	No	VOC	Varies	Varies	Oil & Gas facilities
Local, City of Thornton, CO	Optical Gas Imaging (OGI)	No	Not specified	Monthly, then Quarterly after one year	All detectable emissions	New and existing production facilities

*NSPS OOOOa does not regulate methane from equipment leaks at Gas Processing Plants (VOC only).

Table [SEQ Table * ARABIC]. Applicable Fugitive Emission/Leak Detection Regulations by Segment (Oil & Natural Gas Supply Chain)

Table 4 – Applicable Fugitive Emission/Leak Detection Regulations by Segment (Oil & Natural Gas Supply Chain)											
SEGMENT	**Field Production**					**Process-ing**	**Transmission & Storage**			**Distribution**	
REGULATION	Drilling	Well Completion	Producing Wells	Gathering Lines	Gathering and Boosting Compressor Stations	Gas Processing Plant	Trans-mission Com-pressor Stations	Trans-mission Pipeline	Under-ground Storage	Distribution Mains/ Services	Regulators and Meters
NSPS OOOOa (Federal, EPA)			✓		✓	✓	✓				
NSPS OOOO (Federal, EPA)						✓					
GHGRP, Subpart W (Federal, EPA)	✓	✓	✓	✓	✓						
Waste Prevention and Resource Conservation Rule (Federal, BLM)			✓								
Transmission & Storage Pipeline Safety Rules (Federal, PHMSA)								✓	✓ (pending)	✓	✓
GHG Emission Standards for Oil and Gas (State, California ARB)			✓	✓	✓	✓	✓		✓		
Natural Gas Leak Abatement Rule (State, California PUC)								✓		✓	✓
Underground Gas Storage Requirements (State, California DOGGR)									✓		
Gas Pipeline Requirements (Pending; State, California DOGGR)				✓ (pending)				✓ (pending)			
Regulation No. 7 (State, Colorado DPHE)			✓		✓						
Flowline rule (Pending; State, Colorado			✓	✓							

Table 4 – Applicable Fugitive Emission/Leak Detection Regulations by Segment (Oil & Natural Gas Supply Chain)											
SEGMENT	**Field Production**					**Process-ing**	**Transmission & Storage**			**Distribution**	
REGULATION	Drilling	Well Completion	Producing Wells	Gathering Lines	Gathering and Boosting Compressor Stations	Gas Processing Plant	Trans-mission Com-pressor Stations	Trans-mission Pipeline	Under-ground Storage	Distribution Mains/ Services	Regulators and Meters
OGCC)			(pending)	(pending)							
General Permit 5 (Proposed GP-5A) & Permit Exemption #38 (State, Pennsylvania DEP)			✓		✓	✓ (pending)	✓ (pending)				
General Permits 12.1, 12.2 & 18.1 (State, Ohio EPA)			✓		✓						
General Approval Order for Well Site and/or Tank Battery (State, Utah DEQ)			✓		✓						
Air Quality Standards & Regulations, Chapter 8 (State, Wyoming DEQ)			✓		✓						
VOC Leak Detection Rules (Local, California Air Districts)			✓	✓	✓						
City Regulation CD No. 2017-176 Sec. 18-870 (Local, City of Thornton, CO)			✓								
Upstream O&G Regulations (Pending; International – Canada, Federal)			✓ (pending)		✓ (pending)	✓ (pending)	✓ (pending)				
D-084, Upstream O&G Regulations (International – Alberta, Canada, Provincial)			✓		✓	✓	✓				

3.2 Current Limitations and Needs (Barriers and Opportunities)

Limitations of Regulations

As discussed, there are multiple jurisdictional layers of rules for leak detection and repair requirements at oil and gas facilities throughout the natural gas supply chain. Upstream leak detection regulations are mostly focused on reducing emissions (VOCs and methane) for environmental and health reasons, whereas downstream emission rules, which have been in place longer, are more safety-oriented. Federal rules set a baseline minimum and states and local regions can be more stringent for air quality and climate change regulations. A similar hierarchy generally exists for state and local environmental regulations, though in some states local regulations cannot supersede state requirements.

The system of regulations limits emissions across the supply chain but there are gaps and limitations in the layered, bifurcated system. The transmission and distribution sector considers leak repairs for methane or other air emissions primarily for safety except in limited cases such as the Air Resource Board requirements in California and EPA's New Source Performance Standards (NSPS) OOOOa (USEPA, 2016a), which applies to transmission compressor stations. In practice this means that leaks that are considered non-hazardous for safety reasons, such as in remote areas, need to be monitored but could also continue to leak if they do not meet the definition of a hazardous safety issue. Additionally, storage facilities are not as strictly covered for methane and VOC emissions as production and processing facilities. The recent Aliso Canyon event in California raised concerns about the safety and environmental considerations for these types of facilities.

Production and processing facilities are subject to leak detection and repair requirements both nationally and, in some cases, at the state and local levels. In some cases, these requirements are based on VOC emissions and in some jurisdictions, these measures are part of their State Implementation Plan (SIP) requirements to meet national ambient air quality standards for ozone. As such, any changes in approach must be able to be proven to meet or exceed the level of reductions already achieved. Sources within these sectors that are often exempt from LDAR are non-active wells (idle, abandoned, and orphan), low producing wells, and very heavy oil wells.

In general leak detection is based on two main technologies. Until recently, U.S. EPA's Method 21 was the only regulatory option for compliance with LDAR regulations. However, Optical Gas Imaging (OGI) has now been incorporated into national and some state/local requirements. In addition, some states have alternative technology/method compliance options but criteria for showing equivalency can be either complex or undefined. The two currently accepted leak detection approaches offer advantages and disadvantages. Method 21 is based on easily enforceable concentration standards with a clearly defined protocol for performing leak detection but can be time- and labor-intensive and may underestimate leaks if not performed properly. OGI offers a quicker, more efficient approach to leak detection with the ability to monitor hard-to-reach or unsafe to monitor equipment, but generally has a higher detection threshold than Method 21. Additionally, there is not an established monitoring protocol for OGI like Method 21, although a draft protocol for conducting OGI monitoring was issued by U.S. EPA on September 18, 2015 which references thermal backgrounds, wind speeds, observation distances and limitations on use, such as during rain, fog or extreme cold (USEPA, 2015a). NSPS OOOOa has similar requirements if OGI is used for leak detection but leaves it up to an operator in how to determine maximum viewing distance, wind speed, adequate thermal background, and dealing with adverse monitoring conditions. Note that OGI technology is not allowed for compliance purposes on closed vent systems in U.S. EPA regulations (AWP, NSPS OOOO and NSPS OOOOa). As mentioned, however, OGI may be used to monitor hard-to-reach or unsafe to monitor equipment. As an example of this, the state of Texas issued an alternative means of compliance (AMOC) for a facility in Harris County that allows semi-annual use of OGI technology for monitoring components considered difficult to monitor using Method 21 (AMOC #6) (USEPA, 2015b).

Neither Method 21 nor OGI is currently required in a continuous mode, though some regulations do call out continuous monitoring as an option. Generally, the more frequent or continuous the monitoring, the more likely it is that larger leaks will be identified quickly and their impacts timely mitigated.

Regulatory Development Considerations

Regulators need to achieve several goals when determining the method and standards for implementation. The main objective for air quality related regulations is to reduce emissions to the maximum extent feasible while considering impacts such as cost. Additional considerations when developing rules and considering alternative methods include:

- Cost to regulated entities
- Cost (including training), availability, and transparency of technology for regulatory agencies
- Enforceability:
  - Verification through reporting and inspections
  - Methods of evaluation including standards and methods for clear definitions of violations. Includes consideration of distance from source, weather conditions, and other variables need to be considered.
  - Integration with existing standards and standardized methods
- Meeting both climate and air quality objectives
  - Methods may need to address both greenhouse gases and VOCs
  - Ensuring equivalency with already EPA approved SIP measures
- Community concerns: visualization of leaks, particularly large emission events

As regulators develop and amend regulations, they need significant levels of information. It is more difficult to include a technology if there is a lack of detailed information on the technology or a method for evaluation; insufficient data or case studies to evaluate the performance or compliance status; lack of resources to verify the performance, etc. The technology developer may only provide limited information for competitiveness reasons, which further limits the accessibility and transparency. Regulators need this information and may need non-confidential versions if used for regulatory purposes. Regulators could request additional information or data to support their decisions, which could demand further research, or new data collection for demonstration that takes time and efforts. There is no guarantee of approval but close coordination between technology providers and regulators leads to a smoother process.

In addition to regulation development, existing regulations that include alternative compliance methods have unique challenges to establish equivalent compliance criteria and approving methods or technologies. The smooth review or approval of a new method or technology depends on the process and whether it is established or streamlined. The criteria across jurisdictions could be different. In addition, developers may need to collect more data, or change the functions or specifications to demonstrate performance and compliance with existing technologies or standards. However, many regulators are open to new and evolving technologies as long as they can meet requirements, have an established methodology, can show equivalency, and offer flexible, lower costs alternatives that are enforceable and understandable to regulatory staff. Coordination between regulators and technology developers can help make this process more smooth and understandable to all parties.

Proving technologies in individual sectors and participating in rulemakings and research can also help move technologies forward.

3.2.1 Areas of Opportunity - Legal

The United States EPA and state regulators may issue Consent Decrees / Orders that require VOC emission reductions. Many of the VOC emission reductions have a co-benefit of reducing methane emissions. Some Consent Decrees require the use of leak detection technology that is currently not required by regulations. This gives regulators an opportunity to implement proven technology ahead of regulations.

The USEPA Emission Measurement Group is responsible for updating air emission test methods. Where appropriate the USEPA updates test methods that are technology neutral. The test method specifies the technology performance criteria. Any technology that can meet the performance criteria is acceptable. Examples are provided in Appendix C [insert link]

3.2.2 Other Areas of Opportunity

- In different industry segments (with different typical gas compositions) it may be possible to allow leak detection technologies with limited capabilities. For example, when inspecting equipment carrying predominantly dry gas, it may not be necessary for an alternate technology to be capable of detecting VOC. Programs should remain flexible in approvals depending on the application of the alternate technologies.

- Now is a good time for technology developer to interact with regulators, because the trend is for increased state level action on methane and VOCs. Developers need to take on a more active role in the assessment of the equivalence of their new technologies.

- Participate in EPA or state-funded research or development programs to develop a new technology/method so that all levels have same understanding about the product, meeting the regulatory requirements. Accordingly, the approval process could then be conducted more efficiently.

4 TECHNOLOGY

4.1 Introduction

Many technologies for methane detection exist in the market or are under development. Methane detection technologies have been rapidly evolving in recent years, and this section will describe some of that evolution in a brief review of the history of methane detection. This section will describe some of the recent developments, as well as a template against which future developments can be evaluated. Performance criteria of methane detectors that may be relevant for different applications are described that can then be used to characterize the accepted and emerging methane detection technologies according to their capabilities, limitations, costs, and uncertainties.

4.1.1 History of Methane Detection

Methane leak detection has been performed since natural gas was first captured and transported by pipelines to customers. Originally gas was seen only as a byproduct of producing oil in the 19th century, and gas was burned off at the oil field production. As markets developed for gas, the gas was instead captured and moved to customers, and keeping the gas in the production system became important since gas was then a saleable product. The original leak detection methods applied were simple "audio, visual, and olfactory" (AVO) techniques, wherein an operator of natural gas systems would seek to detect a leak by human observation whenever near their equipment. In certain conditions, and for certain leak sizes, a person can detect the sound of a leak, or the smell of emitted gas, or other visual signals, such as darker deposits left on the equipment near a leak source where heavier condensing components in the gas stream drop out. As pipeline systems grew, AVO techniques were also applied to leak detection for natural gas transmission pipeline routes, where the operator would walk, drive, or fly over the buried pipeline route looking for signs such as dead vegetation or small openings in the ground surface that may indicate a leak area. AVO techniques are still used today, though emission detection devices now offer far superior ability to detect leaks both for above ground and buried pipeline equipment.

As the natural gas systems and pipeline networks grew, so did best practices among natural gas pipeline operators. Often these were then codified by regulatory bodies, so that routine leak detection became a requirement for local distribution systems and transmission pipelines.

Also, after passing of the Clean Air Act in 1970, emissions from other industries that handle more toxic chemicals became a national focus, leading to the development of fugitive detection techniques, such as the US EPA's Method 21, which defined a technique that identified all potential leaking components and used a flame ionization detector (FID) to find hydrocarbons in air around any leaking industry equipment. Though Method 21 was not intended originally for natural gas systems, it did become the standard for leak detection on above ground equipment in other industries and defined a rigorous fugitive emission measurement technique.

Local distribution companies (LDC's) that bring natural gas to consumer's businesses and households have always had a high need for leak detection simply because of the proximity to the public, and the larger consequences of a leak. They have long used a routine leak detection walk with a sniffer device like an FID to seek to detect any leaks in the buried distribution pipeline system. Today, a much wider variety of detection options are already deployed by LDCs.

Similarly, transmission and storage companies have deployed a variety of detection techniques that have been added to their routine pipeline right of way surveys using AVO. Some of these include cameras that can detect increased methane concentrations from aircraft flyovers. In above ground facilities, such as compressor stations, other leak detection techniques have been applied in recent years, such as the Optical Gas Imaging (OGI) cameras that were required to be used under the 2008 Greenhouse Gas Reporting Program (USEPA, 2009). These are described later.

At the farthest upstream, at natural gas producing wells, leak detection devices have been traditionally used only in research projects until the past decade. As these facilities were usually the farthest from the public, they were not as heavily regulated as downstream operations, such as distribution. So upstream was the last segment of the natural gas supply chain to begin to apply leak detection devices. In the past decade, some upstream companies have implemented voluntary leak detection programs using handheld OGI cameras and handheld Tunable Diode Laser Absorption Spectroscopy (TDLAS) devices. In a few states, these have become requirements.

Research did bring new detection developments to the whole supply chain. Staring in the early 1990's, the importance of greenhouse gas impacts of leaks was given additional political consideration, and there became a need to determine the amount of gas leaked by the natural gas supply chain. This lead to development of new national estimates (called emission inventories) of the system, and new field measurements of emissions. In fact, new measurement techniques were developed, such as the HiFlow sampler, because of these efforts. The HiFlow sampler was designed to quantify, rather than just detect, a leak rate. The Hiflow sampler became a commercial product in the 1990s and remains one of the only devices to directly quantify the rate of a found leak.

Commercial enterprises have also produced new detection techniques, such as the Optical Gas Imaging (OGI) cameras commercially offered by FLIR and by Opgal beginning in the early 2000's. These handheld cameras make detection possible by display in a screen, allowing visualization of a gas plume that is otherwise invisible to the naked eye. Other commercial products from a variety of sources use multispectral and hyperspectral cameras for plume detection, such as the Rebellion Gas Cloud Imaging camera. These devices remain expensive and not yet in handheld form, and so are carefully and perhaps sparingly deployed. For ambient air samples, many developments have been made in the past ten years that have increased the accuracy of the determination of the fraction of methane in air. An example is the Picarro Cavity Ring Down system, which has been deployed in many vehicle-based downwind or ambient air studies, including use in distribution system screening vehicles.

In more recent years, the Obama Administration issued its Climate Change Action Plan and Methane Action Plan and thus added political goals for methane detection and emission reduction along the entire natural gas supply chain. The industry has also had other motivations as well, to show that a small enough fraction of gas is emitted so that natural gas would remain the preferred fuel for expansion when considering global warming and greenhouse gas impacts. Research projects were created to develop new detection techniques, such as the ongoing Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR) by the US Department of Energy's Advanced Research Projects Agency – Energy (DOE ARPA-E), and the Methane Detectors Challenge by the Environmental Defense Fund. Both of these efforts had specific goals to produce new detection techniques that were much less expensive and that could perform continuous monitoring.

In addition to sponsored research efforts, development of independent commercial technologies continues by individual companies. These vary from open path approaches such as Boreal Laser to systems that aim to add quantification to OGI camera image captures, such as Providence Photonics quantitate OGI (QOGI) systems. In future years, these research efforts, and the development efforts of independent commercial enterprises are expected to produce new detection devices and offerings.

4.1.2 Classification Scheme

This review has added a classification approach for evaluating different technologies, so that currently existing commercially offered technologies can be compared to technologies that are currently being developed, or those that may emerge in the future. The classification approach used in this document compares the technologies by result type, data type, time period covered in a measurement, size, working distance, deployment method, relative cost, measurement limitations, as well as other features such as safety, interferences, durability, and other ancillary benefits. Each of these comparison categories is discussed briefly below.

Primary Data Type. Different systems may present data in various formats. Quantitative systems will produce a numerical value, such as ppm or a leak rate g/hr. Qualitative systems may provide data in different formats, such as a video image, or a processed image from an Optical Gas Imaging camera.

Result Type. Results from emission sensing and measurement devices are generally in one of three categories. 1) “Qualitative” systems provide a leak or no leak detection, but do not provide emission rate quantification; 2) “Quantitative (concentration)” systems generally provide a concentration of the emitted species in air, such as a parts-per-million (ppm) reading, or concentration-pathlength readings (e.g. ppm-meter), but do not inherently provide emission rate quantification; and 3) “Quantitative (emission rate)” systems provide a measurement of the actual emission or leak rate, such as g/hr. If the desired end result is a quantification of emission rate, it must be understood that a “quantitative (concentration)” system does not provide that result.

It is important to note that certain “platforms for deployment” may use simple quantitative (concentration) data from detectors to calculate or estimate a quantitative (emission) rate. Examples of these platforms are:

- deployment platforms that use some simplified inverse dispersion modelling to estimate an emission rate when only quantitative (concentration) data is gathered. The quantitative (concentration) data may be from a single source sample or a distributed network of detectors.
- deployment platforms that use box models over large areas, with measured inlet concentrations into the box and measured outlet concentrations from the box, in order to perform a mass balance, and then calculate the net emission rate inside the box. This is commonly used in some aircraft-based approaches deployed over single sites or much larger geographic areas.
- deployment platforms that measure downwind concentrations of the species of gas being emitted as well as a known release rate of a tracer gas, and then assuming equal dispersion, calculating the estimated release rate of the emitted gas by simple ratio to the tracer gas.
- deployment platforms such as Providence Photonics QL320 tablet that uses qualitative measurements of infrared radiance changes caused by gas plume and detected by a

radiometrically calibrated OGI camera (such as FLIR GF320), combined with bench test data from known emissions to estimate an emission rate.

Since this section evaluates the detector, and not the platform, only the result type from the detector will be classified.

Measurement temporal resolution. This may also be called "sampling rate". The detector may produce a discreet result that is, or can be, repeated after a set time interval. That time interval is the temporal resolution. Better resolution would mean more frequent readings, whereas poorer temporal resolution would mean less frequent readings. Temporal resolution may not be important for all measurements, especially those that only require a single sample.

Size. This basically describes the device size, which has some implications for how it can be deployed. Some of the size categories are: 1) "small" (such as small distributed printed card detectors); 2) "handheld" which would apply to equipment portable by one person, such as the HiFlow backpack, some of the Optical Gas Imaging cameras, or the TDLAS device by Heath called the Remote Methane Leak Detector (RMLD), 3) large, which would include devices that have to be "vehicle based" such as some of the larger equipment driven in ground vehicles or airplanes, like as the Picarro cavity ring down system, or the Rebellion Gas Cloud Imaging system.

Deployment Method. This describes the normal means of deployment for the system. Some systems may be deployable in multiple methods. These can be: 1) "walking" for handheld devices; 2) "vehicle path" for airplane or vehicle-based systems; 3) or "fixed location" for some systems. Some systems may be deployed in downwind ambient air measurements only, while some may be applied directly at the emission location.

Specificity/ Speciation. This relates to whether the instrument is focused only on methane or whether it will also produce a result that includes other hydrocarbons.

Working Distance. Working distance refers to the minimum and maximum distance that a technique can be used. This will vary by the detection limit desired for the regulatory purpose. For example, the detection abilities of OGI cameras are known to diminish with distance; the closer they are to the leak, the smaller the leak they can see. OGI cameras are normally deployed as handheld screening devices by an operator walking around a facility, and therefore used in the 2 ft to 50 ft range from any source. In this range, they have a certain threshold for minimum leak size that can be detected. However, they can be deployed from much farther away, such as in an aerial flyover of several hundred feet, if the user is willing to accept a poorer (higher) minimum threshold of leak detection. Some techniques, such as the flame ionization detector used for EPA's Method 21, require extremely close proximity (close to 1 cm), while others, such as Rebellions GCI camera, require a much longer setback farther than the OGI camera. Finally, some methods, such as the HiFlow device requires direct contact and partial enclosure; the distance is effectively zero.

Environmental Limitations. These will list, in text format, any known limitations for the method. This includes atmospheric delta temperature limitations for the OGI camera that means not all days nor all times of day are suitable for measurement or the need for stable winds to transport plumes to the measurement point.

Calibration Procedures. Calibration procedures list the frequency of required calibrations and the duration and level of effort required for said calibration.

Maturity/Technology Readiness Level (TRL). Maturity will be listed as: 1) research; 2) development/evaluated; 3) single source, or 4) multiple source. Research is for technology that has undergone testing in the laboratory environment. Development/evaluated is for technology that has undergone field testing and has been considered as a viable technology for regulatory or industrial use. Single source is a technology that is commercial available from vendor but is limited to a single vendor due to intellectual property (IP) or market considerations. Multiple source is a technology that is commercial available from multiple vendors. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology (EARTO, 2014).

Miscellaneous: Durability, Service Factors, Safety Ratings, and Maintenance Requirements. This miscellaneous category will describe issues that may differentiate a system, such as frequent calibration requirements vs no calibration requirements, or known high or low service factors for particular systems. Some devices will also have a safety rating classification that makes them intrinsically safe even in environments that contain flammable gases; such a rating may be important for certain applications. These will be spelled out.

Accuracy. This is the closeness of a measured result to an accepted reference value or true value. Accuracy formula expressed in terms of error (also known as uncertainty):

$$\text{Accuracy (expressed as \% Error)} = \frac{|(\text{True Value} - \text{Measured Value})|}{\text{True Value}} \times 100$$

4.2 Technologies

This section summarizes the known existing technologies as well as some emerging technologies using the technology classifications presented in Section 4.1.1 to describe them. An overview table is provided to summarize the current technologies and then each technology is discussed in greater detail. Section 4.2.3 then discusses different applications for the technologies.

4.2.1 Current Technology Overview

Table 5 below summarizes the known methane detection technologies using some of the technology classifications presented earlier.

Table [SEQ Table * ARABIC]. Summarizing Examples of Technology/Applications

Technology	Primary Data type	Deployment Method	Specificity/ Speciation	Working distance	Calibration Procedures	Device Examples
Pellistor (Catalytic Bead)	Quantitative gas concentration	Portable, hand held, fixed	nonspecific; cross sensitivity to VOC's	Point measurement	Calibration gas. Typical calibration period is between weeks to months depending on exposure.	SGX - SensorTech: MP-7217-TC Combined Flammable and Volume Percent Methane Sensor

Technology	Primary Data type	Deployment Method	Specificity/ Speciation	Working distance	Calibration Procedures	Device Examples
Metal Oxide Semi-conductor (MOS)	Quantitative (concentration)	Portable, Hand held, or Fixed	nonspecific; cross sensitivity to VOC's	Point measurement	Calibration gas. Frequent calibration is required.	
Flame Ionization Detector (FID)	Quantitative (concentration)	Portable, Hand held, or Fixed	Hydrocarbons	Point measurement	NiMH rechargeable pack	DataFID™ Portable Flame Ionization Detector and the MicroFID™ II Portable Flame Ionization Detector
Gas Chromatography (GC)	Quantitative gas concentration or Qualitative response chart dependent	Portable and Fixed	methane.	Point measurement	Calibration gas. Typically, a calibration check and purge is required prior to use. Calibration frequency varies based on the instrument design.	The Agilent 490 Micro GC
High Volume Dilution Sampling	Quantitative, both concentration and emission rate		Any hydrocarbon that can be oxidized will produce a reading	2 m, as limited by the length of the HiFlow air intake hose		
Mass Spectrometry	Quantitative/Qualitative (concentration)	fixed.	organic and inorganic samples down to sub-ppt levels	cavity measurement		LECO - Pegasus GC-HRT+
Printed Nanotubes Sensors	Quantitative (concentration)	fixed.	?	?	More testing will be required before operational calibration requirements are finalized	?
Dual Frequency Comb Spectroscopy	Quantitative (concentration)	fixed.	Ultra-High spectral resolution and specificity of molecules.	Local measurement up to 2 kilometers		erbium-doped fiber frequency combs
Single-Pass Tunable Laser Absorption Spectroscopy	Quantitative gas concentration.			Variable, depends on the path length of absorption. Point measurement		
Multi-pass Tunable Laser Absorption Spectroscopy	Quantitative gas concentration		1–5000 ppm	Point measurement	calibration gas	
Cavity Ring Down Spectroscopy	Quantitative gas concentration	Portable and Fixed	methane in ppbv to pptv	cavity measurement	Several months (or in some cases over a year) before any re-calibration is required. Also rechargeable Li-ion battery pack for portable devices.	Picarro -GasScouter™ CH4, C2H6 and H2O Analyzer, and Picarro G2204 Methane / Hydrogen Sulfide Analyzer
Integrated Cavity Output Spectroscopy (ICOS)	Quantitative gas concentration	fixed.	methane	cavity measurement		
Bistatic	?	?	?	?	?	?

Technology	Primary Data type	Deployment Method	Specificity/ Speciation	Working distance	Calibration Procedures	Device Examples
Monostatic	Quantitative gas concentration	fixed unmanned	methane ppm		Various and architecture dependent – a) By introduction of known concentration mixture in the cell or b) Calibration-free mode. Not possible to do primary calibration due to large measurement path	
Backscatter	Quantitative gas concentration	portable hand-held, fixed	methane. 0 to 99,999 ppm-m	100 ft (30 m) nominal. Actual distance may vary due to background type and conditions.	rechargeable, Li ion battery pack	Remote Methane Leak Detector (RMLD-IS®)
Range Resolved DIAL	?	?	?	?	?	?
Etalon	Quantitative gas concentration	Fixed, portable, mobile	.2ppm to 2000ppm	Point measurement	built in calibration cell typical; operational temperature calibration is performed as needed.	
Optical Gas Imaging	Qualitative (Image)	Portable, Hand held, or Fixed	Hydrocarbons	Field of View of instrument	Rechargeable Li-ion battery	Many FLIR Products, and the Providence Photonics QL320™ / QL100™
Open Path Fourier Transform Infrared (FTIR) Spectroscopy	Quantitative gas concentration / Quantitative Gas Image	Portable and Fixed	effective spectral resolution < 0.0007 cm-1 and spectral range up to 3-50000 cm-1	Local measurement up to 1 kilometer	An internal calibration source provides automated radiometric calibration	BRUCKER - FT-IR spectrometer / monitoring / automated / OP-FTIR, and the BRUCKER Gas detection system / FT-IR / long-distance and the The AirSentry FTIR
Gas Filter Correlation Radiometer	Quantitative Concentration/Emission rate	Airborne (airplanes & drones) & Spaceborne (microsatellite constellations)	methane. < 1% natural abundance, 100 ppm-m integrated concentration,	Variable long path remote sensor (Depends on instrument and configuration). Airborne (aircraft or drone): Min working distance = 10 m, Max = 300 m (1000') Spaceborne platforms: Low Earth Orbit (500–600 km)	Instruments are self-calibrated type on sensors for Quantitative Concentration measurements. Required sparse periodic ground reference ancillary calibration measurements (e.g. ground reference winds) for Quantitative Emission Rates measurements.	

4.2.2 Technology Descriptions

4.2.2.1 Pellistor (Catalytic Bead)

Description:

Pellistor sensors are based on the reaction between VOC or Hydrocarbon gas and a catalyst material. The catalyst promotes oxidation of the gas. Often a reference element is used to compensate for environmental conditions such as ambient temperature and humidity. The Pellistor element is heated to the point that the target gas burns, causing a change in the element resistance. The amount of resistance change is proportional to the gas concentration.

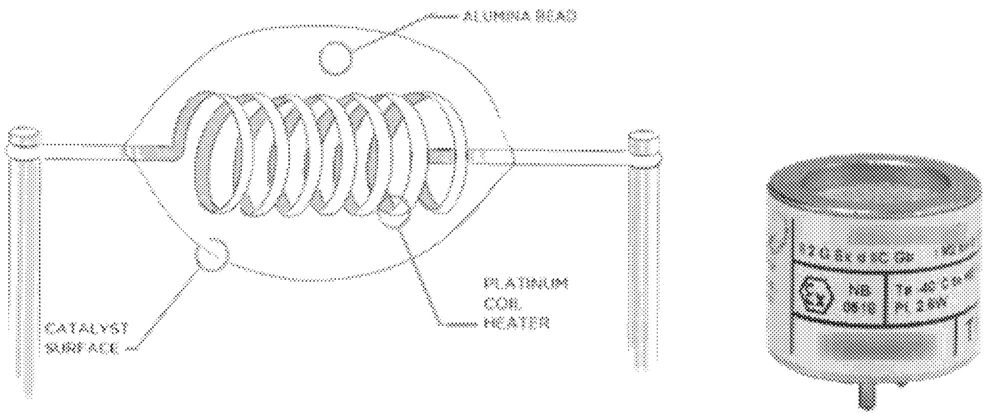

Figure [SEQ Figure * ARABIC]. Drawing and illustration of an element

Source: Heath Consultants

Copywrite Permissions – START HERE with Figure 3 above

Characteristics:

1. Primary Data Type: Analog voltage level
2. Result Type: Quantitative gas concentration
3. Detection Range: Low percent gas by volume. Typical instrumentation range from 500 ppm to 5% v/v methane. Accuracy is typically in the ±10% of reading.
4. Specificity/Interference: nonspecific; cross sensitivity to VOCs
5. Other Benefits: Low cost sensors are widely used throughout industry
6. Measurement intermittency: Continuous
7. Measurement temporal resolution: Hz
8. Size: Small
9. Deployment Method: Portable, hand held, fixed
10. Working Distance: Point measurement
11. Environmental Limitations: Humidity, temperature, contaminates
12. Calibration Procedure: Calibration gas. Typical calibration period is between weeks to months depending on exposure.
13. Maturity/TRL: Mature
14. Durability, Service Factors, and Calibration and Maintenance Requirements: Sensors have a short life depending on level of contaminates it is exposed to. Sensors may be damaged by shock or vibration. Loss of sensitivity when exposed to organic materials. Exposure to high gas concentrations may reduce sensor life.

Mode of use:

Catalytic Bead Pellistor is suitable for leak detection of VOCs and hydrocarbons. It is non-selective to the gas species. Typically, the technology is used as a portable gas detection instrument or in fixed monitor applications. This sensor technology is most often used in combustible gas indicators and personal protection devices for the measurement of explosive levels of gas.

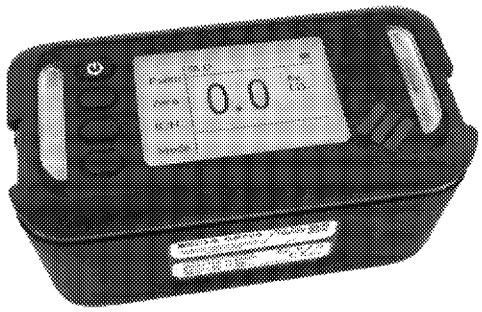

Figure [SEQ Figure * ARABIC]. Portable combustible gas indicator

Source: GMI

4.2.2.2 Metal Oxide Semi-conductor (MOS)

Description:

Metal Oxide Semi-conductor (MOS) sensors are semiconductor circuits specifically doped with oxide materials that will react to the intended target gas. Tin dioxide is commonly used for methane and VOC detection. When gas particles react with the oxide material, a change in resistance of the sensor occurs. The amount of resistance change is proportional to the gas concentration. Often the sensor includes a heating element to raise the sensor temperature to minimize the effect of water vapor and to maximize the reaction to the target gas.

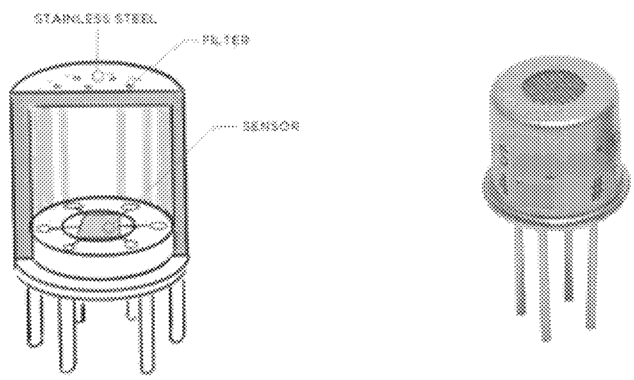

Figure [SEQ Figure * ARABIC]. MOS sensor element

Source: Heath Consultants

Characteristics:

1. Primary Data Type: Quantitative
2. Result Type: Quantitative gas concentration
3. Detection Range: Typical sensors have sensitivities in the range of 50 ppm depending on the specific sensor design.
4. Specificity/Interference: Nonspecific; cross sensitivity to VOCs
5. Other Benefits: Low cost sensors are widely used throughout industry
6. Measurement intermittency: Continuous
7. Measurement temporal resolution: Hz
8. Size: Small
9. Deployment Method: Portable, Hand held, Fixed
10. Working Distance: Point measurement
11. Environmental Limitations: Humidity, temperature, contaminants
12. Calibration Procedure: Calibration gas. Frequent calibration is required. Upon power, sensor must zero on the ambient air condition.
13. Maturity/TRL: Multi-source/Evaluated
14. Durability, Service Factors, and Calibration and Maintenance Requirements: MOS sensors will react to a wide range of different gases. Often false readings are experienced by rapid change in the ambient air (e.g. moisture and temperature). Exposure to high gas concentrations may de-sensitize the sensor lasting for a prolonged period or may have irreversible change to its zero-gas reading or sensitivity. Exposure to basic or acidic compounds, silicones, sulphur and halogenated compounds may have significant irreversible effect on sensitivity. High oxygen concentrations may have significant irreversible effect on sensitivity.

Mode of use:

MOS is suitable for leak detection of VOCs and hydrocarbons. It is non-selective to the gas species, and is highly responsive to other gases. Typically, the technology is used as a portable gas detection instrument. This sensor technology is most often used for applications which don't require very high sensitivity and don't have high gas concentrations. Often the sensor is used to "sniff" around fittings.

Figure [SEQ Figure * ARABIC]. Portable gas indicator with MOS sensor tip

Source: GMI

4.2.2.3 Flame Ionization Detector (FID)

Description:

Flame Ionization is a sensor technology which measures the relative gas concentration through a method of passing the sample air through a combustion chamber were the sample gas is burned at high temperature in a clear hydrogen flame. VOC and hydrocarbon molecules are charged through the burning process to become ions. The positive charged ions are then collected onto an electrode. The amount of positive charge on the electrode is then proportional to the gas concentration.

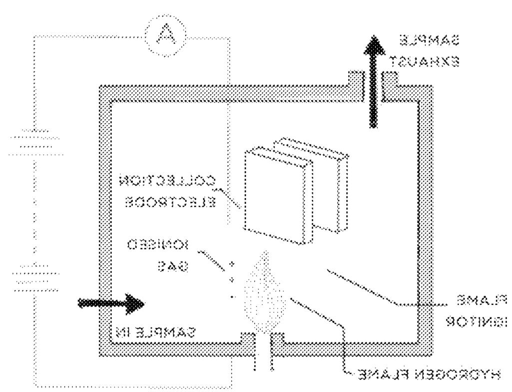

Figure [SEQ Figure * ARABIC]. FID cell

Source: Heath Consultants

Characteristics:

1. Primary Data Type: Analog voltage level
2. Result Type: Quantitative gas concentration
3. Detection Range: Typical sensors < 5ppm depending on the specific sensor design.
4. Specificity/Interference: Nonspecific; cross sensitivity to VOCs
5. Other Benefits: Low cost sensors are widely used throughout industry
6. Measurement intermittency: Continuous
7. Measurement temporal resolution: Hz
8. Size: Medium instrument (7 lbs. (3.2 kg)) and telescopic probe extends from 25 to 41 inches (63 cm to 104 cm); 1 lb. (.45 kg)
9. Deployment Method: Portable, Hand held, Fixed
10. Working Distance: Point measurement
11. Environmental Limitations: Humidity, temperature, contaminants
12. Calibration Procedure: Calibration gas. Frequent calibration is required with a field calibration kit. Upon power, sensor must zero on the ambient air condition.
13. Maturity/TRL: Mature
14. Durability, Service Factors, and Calibration and Maintenance Requirements: FID is not suitable for detection of carbon monoxide and inorganic gases. High gas concentration will cause a flame out. Halogenated hydrocarbons reduce the sensor response and will affect the measurement of the total hydrocarbon concentration.

Mode of use:

FID is suitable for leak detection of VOCs and hydrocarbons. It is non-selective to the gas species. Typically, the technology is used as a portable gas detection instrument. Instruments require the use of hydrogen fuel carried in small DOT compliant cylinders. Typically, the hydrogen fuel cylinders are restricted from being transported on airplanes and tunnels.

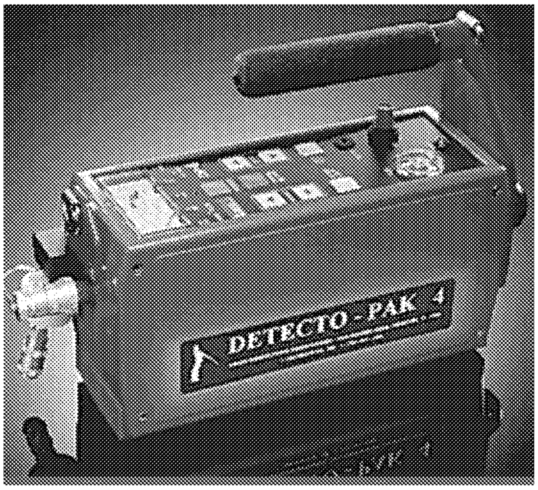

Figure [SEQ Figure * ARABIC]. FID gas leak survey instrument

Source: Heath Consultants

4.2.2.4 Gas Chromatography (GC)

Description:

Gas Chromatography (GC) is a system used to separate different species of gases which are then detected via other detection technologies (e.g. with FID). A typical system consists of a gas injection port, carrier gas port, separator column, detection sensor and a time chart. The separator column is often heated.

As gas passes through the separator column, the gas components will separate from each other based on their molecular weight (MW), since higher MW gases take longer to pass through the column. As the gas exits the separator and passes through the detector, a signal vs. time trace is created. The timing of the various peaks will indicate the type of gas. The gas concentration required to make measurements vary significantly based on the instrument design. Highly sensitive systems are typically found in laboratory instruments. Portable instruments typically require higher gas concentration. Response rate is slow and varies based on the design of the separator.

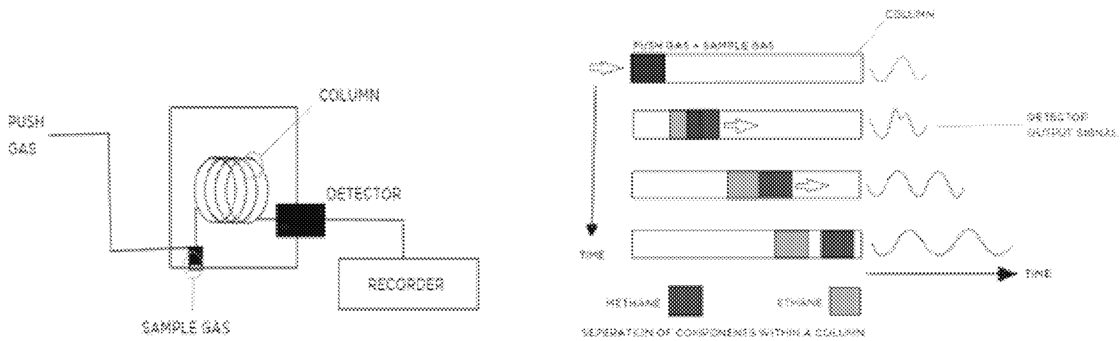

Figure [SEQ Figure * ARABIC]. Example gas transport and column separator. Gases of different weight transport through the column at different speeds.

Source: Heath Consultants

Characteristics:

1. Primary Data Type: Analog voltage level over time
2. Result Type: Quantitative gas concentration or Qualitative response chart dependent on design
3. Detection Range: varies significantly depending on design (ppb to %)
4. Specificity/Interference: not applicable
5. Other Benefits: Field instruments quickly help to determine source of gas leak
6. Measurement intermittency: Discrete sample
7. Measurement temporal resolution: 100Hz or longer
8. Size: From handheld to laboratory fixed installs
9. Deployment Method: Portable and Fixed
10. Working Distance: Point measurement
11. Environmental Limitations: Minimum gas concentration required for measurement
12. Calibration Procedure: Calibration gas. Typically, a calibration check and purge is required prior to use. Calibration frequency varies based on the instrument design.
13. Maturity/TRL: Mature
14. Durability, Service Factors, and Calibration and Maintenance Requirements: Clean dry carrier gas is typically required.

Mode of use:

Both portable and fixed systems are commercially available. Portable instruments are often used to identify the possible source of the gas. For example, natural gas will contain a percentage of ethane. Therefore, to determine if a underground gas leak is from a natural gas pipeline or from a biological source, a portable GC is used to determine if ethane is present.

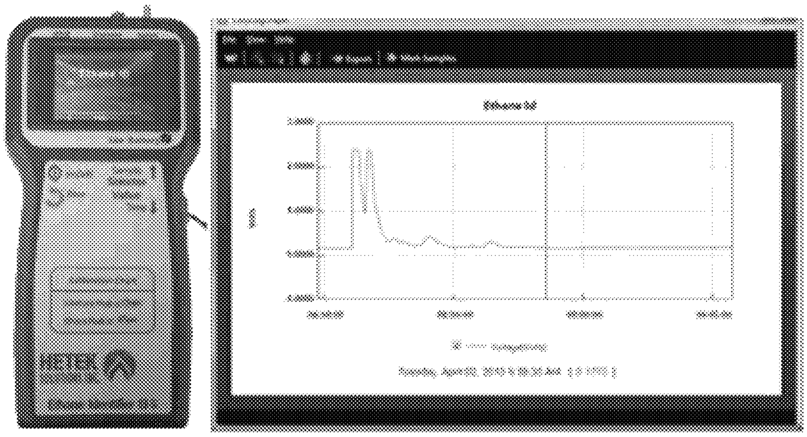

Figure [SEQ Figure * ARABIC]. Portable ethane identifier for discriminating natural gas containing ethane

Source: Hetek supplied by Heath Consultants

4.2.2.5 High Volume Dilution Sampling.

Description:

This is an emission rate quantification approach that measures an individual emission rate (such as a leak at a single component) by drawing in a source's total emissions with a larger air flow. The induced air flow is at a known and measured rate and is assumed to capture the entire leak of concern. By determining the concentration of the leaked species in the air flow, the total emission rate of the leak can be calculated. The only commercially offered high volume model was the Bacharach Hi Flow Sampler™, a portable instrument used to measure continuous leak emission rates of gaseous hydrocarbons such as methane. The device has been commercially available for 20 years and used in many studies and leak-detection-and-repair (LDAR) programs in the natural gas supply chain. Manufacture of the Bacharach device was discontinued in late 2016 when the patent expired, but it is still widely used in the natural gas industry.

Characteristics:

1. Primary Data Type: Concentration Sensors. The Hi Flow Sampler™ utilizes two sensors, a catalytic oxidation sensor for gas concentrations ranging from 0 to 5% by volume of methane, and a thermal conductivity sensor for gas streams containing higher methane concentrations.
2. Result Type. Quantitative, both concentration (ppm in the induced air flow) and emission rate (l pm or scfm) determined through instantaneous calculation (primary data).
3. Detection Range: 1.42 to 226 liters per minute.
4. Specificity/Interference: Any hydrocarbon that can be oxidized will produce a reading, and a specific gas speciation of the emitted gas may be needed in order to correct the HiFlow.
5. Other Benefits.
6. Measurement intermittency. Measurement is nearly continuous, but data recording is manual, and therefore is on a snapshot basis.

7. Measurement temporal resolution: There is no temporal resolution on a commercial HiFlow, other than the frequency of recorded emissions made by the operator. Some researchers have altered the device to record nearly at a 1 Hz frequency.
8. Size. Backpack sized.
9. Deployment Method. Portable, carried to each leak.
10. Working Distance. Two (2) meters (m), as limited by the length of the HiFlow air intake hose
11. Environmental Limitations.
12. Calibration Procedure: Using 2.5% methane gas and 99% methane gas;
13. Maturity/TRL: Mature
14. Durability, Service Factors, and Calibration and Maintenance Requirements. There have been published concerns about HiFlow use for natural gases with low methane concentrations (and correspondingly high VOC concentrations (Howard, 2015).

Mode of use:

The leak rate measurement is conducted by placing the instrument hose inlet in a manner that captures the emission source being sampled, with the concept being that the instrument draws in enough excess air to capture the entire leak. Compared to other concentration sampling devices that simply measure concentration in a very small sample of air, the instrument draws in a very large flow rate of air (between 5 and 10.5 cfm for the HiFlow), with the result that the device can calculate an emission rate from the known air flow and the measured concentration. This approach does assume that the entire emission rate is captured, which can be tested by allowing the device to pull in less air and check to see that it still calculates the same emission rate.

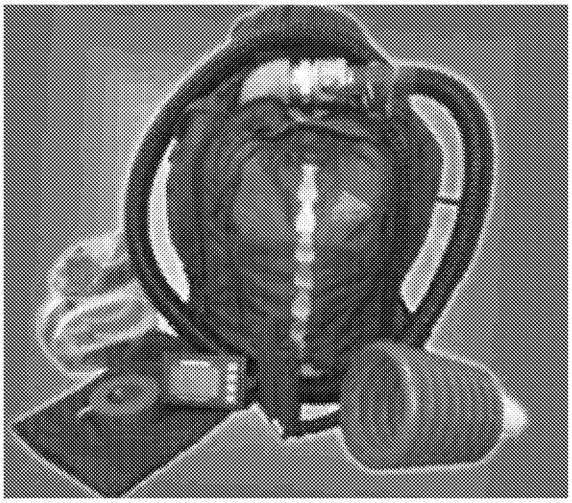

Figure [SEQ Figure * ARABIC]. High Flow Sampler

Source: Heath Consultants

4.2.2.6 Mass Spectrometry

Description: Mass spectrometry (MS) identifies and quantifies molecules in simple and complex mixtures and helps to elucidate ion-molecule interactions. Often mass spectrometry is used in tandem with gas or liquid chromatography to improve the specificity/selectivity of the method. The applications of mass spectrometry range from forensic analysis, isotope dating and tracking, trace gas analysis, clinical research, proteomics, lipidomics, metabolomics to monitoring environmental pollutants and determining methane emissions.

All mass spectrometers measure the mass-to-charge (*m/z*) of an analyte. There are a variety of approached used to determine mass to charge include quadrupole mass analyzer, ion traps, and time-of-flight mass analyzers. These systems use a multitude of ionization sources, such as electron impact (EI), chemical ionization (CI), and electrospray ionization (ESI), to produce ions that are detected by the instrument. Mass spectrometry is a relatively mature field with robust instruments in laboratory and field settings.

Characteristics:

1. Primary Data Type: Mass-to-charge ratios (m/z) and their relative abundance
2. Result Type. Qualitative and quantitative (amount, concentration)
3. Detection Range: Variable, commercial systems are capable of sub-ppb to percent level determinations, depending on configuration and the mode of operation.
4. Specificity/Interference: Function of resolving power of the system, low resolution systems will have lower specificity than higher resolution system. If auxiliary systems are added, i.e., gas chromatography (GC), specificity can be improved.
5. Other Benefits. Isotope ratio mass spectrometers are able to distinguish thermogenic and biogenic methane sources.
6. Measurement intermittency. Depending on the units from continuous to intermittent.
7. Measurement temporal resolution: System dependent and varies from <1 Hz to continuous.
8. Size. From handheld to floor base units.
9. Deployment Method. Handheld to permanent installations in laboratories. Fixed, fence line.
10. Working Distance. Sample must be presented to the instrument; potential to use a tether.
11. Environmental Limitations. Dependent on instrument's ruggedization, could be made to work in any environmental condition.
12. Calibration Procedure: Software-based calibration routine, per manufacturer instructions.
13. Maturity/TRL: Mature for general MS and some field-based applications. Generally developmental to mid-TRL for methane detection systems.
14. Durability, Service Factors, and Calibration and Maintenance Requirements: Dependent on the system.

Use:

Mode of use: A solid, liquid, or gas sample is ionized, i.e., by bombarding with electrons, mass analyzed, and detected, see Figure [Schematic of mass spectrometer operation ([HYPERLINK "http://cnx.org/contents/85abf193-2bd2-4908-8563-90b8a7ac8df6@9.58:12/Atomic-Structure-and-Symbolism"] ***from Openstax,*** [HYPERLINK "https://creativecommons.org/licenses/by/4.0/"]]. The *m/z* ratio is plotted vs. its relative abundance producing mass spectrum, see Figure [***Mass spectrum of methane (***[HYPERLINK "http://webbook.nist.gov/chemistry"]]

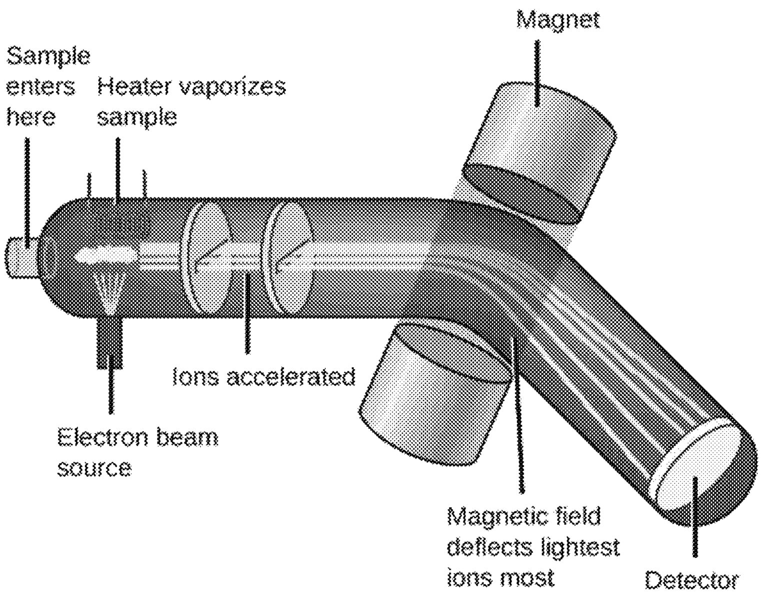

Figure [SEQ Figure * ARABIC]. Schematic of mass spectrometer operation

Source: Openstax, [HYPERLINK "https://creativecommons.org/licenses/by/4.0/"]. [HYPERLINK "https://creativecommons.org/licenses/by/4.0/"]

[HYPERLINK "https://cnx.org/contents/havxkyvS@9.58:ZV-IsnqQ@8/Atomic-Structure-and-Symbolism"]

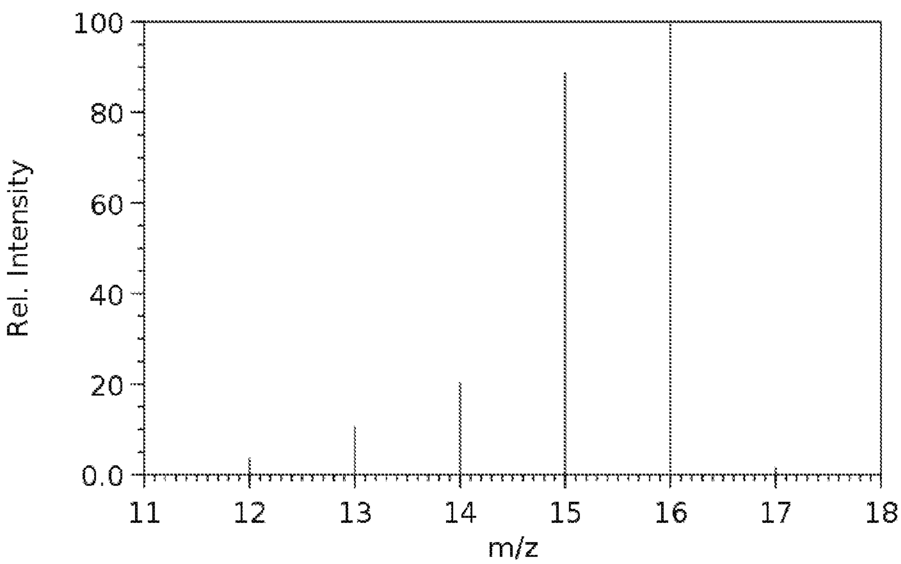

Figure [SEQ Figure * ARABIC]. Mass spectrum of methane

ED_004016P_00001169-00048

Source: National Institutes of Standards and Technology [HYPERLINK "http://webbook.nist.gov/chemistry"]

Performance:

The response time and sensitivities are very dependent on the type of the instrument and its design. For example, inductively coupled plasma mass spectrometry (ICP-MS) can identify and characterize some metal-containing samples down to sub-ppt levels. The response time can be as short as sub-seconds.

Calibration:

Mass spectrometry uses calibration compounds, which provide ions of known *m/z* ratios, that are used to correct the mass and intensity scales. The calibration compound is dependent on the instrument, application, and desired mass analysis range.

Limits of Use:

There are several limitations of MS (1) All mass spectrometers require a vacuum system. Some system required a demanding vacuum system while some newer technologies reportedly use minimal vacuum systems (2) Structural isomers are generally distinguishable while stereoisomers can be difficult to distinguish; (3) The EI fragmentation patterns for some classes of hydrocarbons (e.g. n-alkanes) are highly conserved making absolute identification of the molecule difficult. Tandem techniques (e.g. addition of chromatographic systems) are frequently used to characterize complex hydrocarbon samples.

A variety of miniature and field-portable mass spectrometers are currently under development. As an example, the coded aperture miniature mass spectrometer environmental sensor (CAMMS-ES) is being developed as a methane monitoring system. The instrument is capable of continuous sampling and has increased specificity and sensitivity for the detection of methane and other volatile organic compounds (VOCs).

4.2.2.7 Printed Nanotubes Sensors

Description:

Printed nanotube sensors consist primarily of functionalized and/or doped carbon nanotubes (CNTs) that can provide detection of a range of atmospheric species, including methane. Methane molecules are passively transported to the CNTs and change the electrical response of the CNT, which can be detected and converted to a methane concentration. Functionalizing the CNTs with a wide variety of substituents allows for detection of a variety of species. Due to the low cost of the raw materials and small amounts required when combined with scalable manufacturing approaches, sensor costs can be quite low. Research is on-going to determine the limits of this technology and determine chemical and engineering solutions, including the fabrication of a matrix of sensors with various calibrations to speciate and quantify a wide variety of compounds.

Characteristics:

1. Primary Data Type: Quantitative (concentration)
2. Result Type. Quantitative, both concentration (ppm) and emission rate (g/hr) possible through modeling (secondary data).
3. Detection Range: <1 ppm to 100+ppm
4. Specificity/Interference: Design-specific; Interference is difficult to mitigate without a robust variety of sensors, calibrations for each sensor and compound, and advanced computational algorithms.
5. Other Benefits. Can be made into an array with potential to detect other hydrocarbons, thus distinguish thermogenic or biogenic methane sources.
6. Measurement intermittency. Continuous
7. Measurement temporal resolution: Depends on design, can be 1 – 100 minutes
8. Size. Small A few inches on a side.
9. Deployment Method. Sensors are relatively small and can be placed in a wide variety of locations, just need a place and means of affixing them.
10. Working Distance: No specific minimum working distance; max working distance determined by limit of detection.
11. Environmental Limitations. High humidity can be challenging.
12. Calibration Procedure: More testing will be required before operational calibration requirements are finalized – likely to include relatively frequent 'baseline' calibrations using the electrical circuitry, as well as occasional calibration by flowing a known concentration of gas, or a series of gases, over the sensor for a short period of time.
13. Maturity/TRL: Research/Feasibility stage – TRL 4 (EARTO, 2014).
14. Durability, Service Factors, and Calibration and Maintenance Requirements. More testing with finalized sensors will be required before exact durability, service factors, calibration, and maintenance requirements are determined.

Mode of use:

The sensors can be affixed to a variety of surfaces or attached to poles surrounding operations. As the wind direction shifts, a methane plume will be transported in the direction of the sensor. The sensor will read a concentration increase in ambient methane. A number of these sensors can be distributed across a wellhead, pipeline, compressor station, or other oil and gas operations. Combining the signals may provide information about the source and magnitude of the emission.

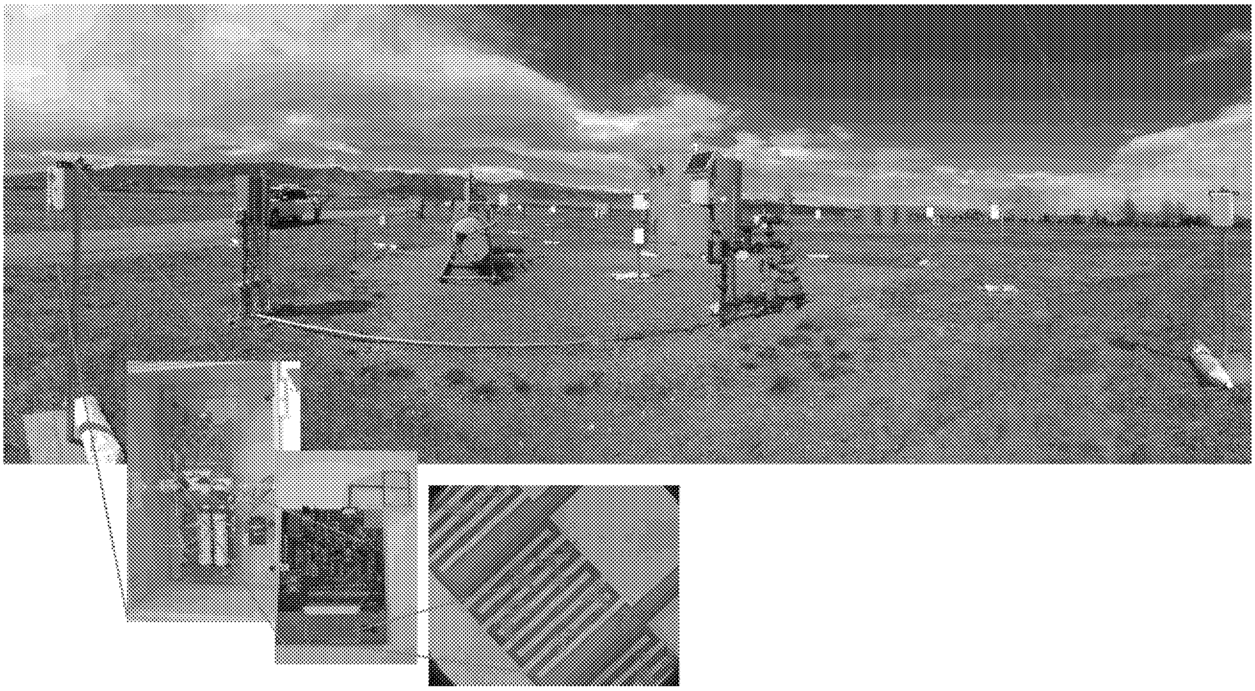

Figure [SEQ Figure * ARABIC] - PARC Nanotube Sensor

Source: Images are provided courtesy of PARC, a Xerox company

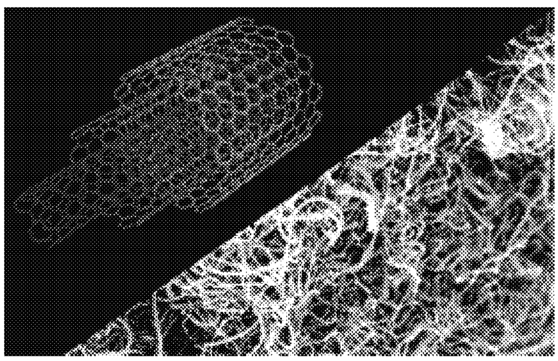

Figure [SEQ Figure * ARABIC]. Photo of carbon nanotubes. Produced as tangled bundles, multiwalled nanotubes are concentric layers of cylindrical carbon lattices.

Source: Bayer MaterialScience

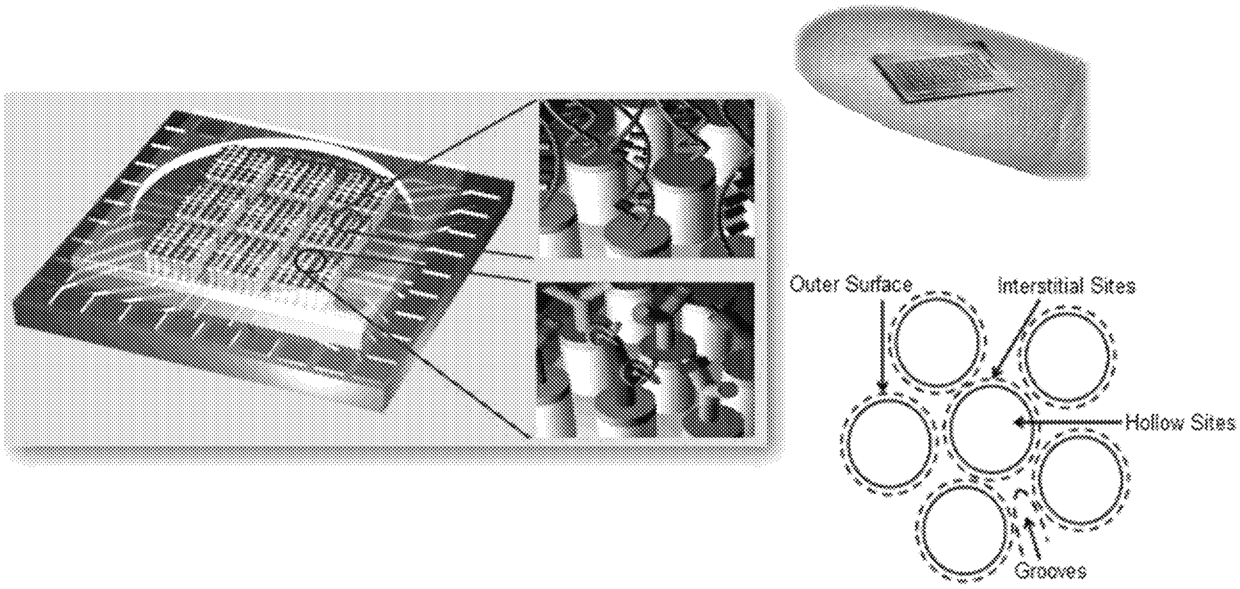

Figure [SEQ Figure * ARABIC]. Nanotube Sensor

Source: Chattopadhyay, S. (2008) Application of Nanomaterials for Environmental Monitoring, Remediation and Challenges. International Environmental Nanotechnology Conference: Applications and Implications. October 7-9, Chicago, Illinois.

4.2.2.8 Dual Frequency Comb Spectroscopy

Description: Dual frequency-comb spectroscopy (DCS) for detection of suite of chemicals with high spatial and temporal resolution. Current DCS technologies are based on probing molecules in the mid infrared region of the spectrum which is the fingerprint region of most molecules. DCS provides broad tunability with high spectral resolution, fast measurements and high brightness which enable applications which are not feasible using thermal sources. DCS has broadband spectral coverage for multispecies detection, a bright diffraction-limited source for high signal-to-noise ratio (SNR) over multikilometer ranges, a rapid update rate for immunity to turbulence-induced optical intensity fluctuations, and, importantly, can sample the transmission on a comb tooth-by-tooth basis for high-accuracy spectra.

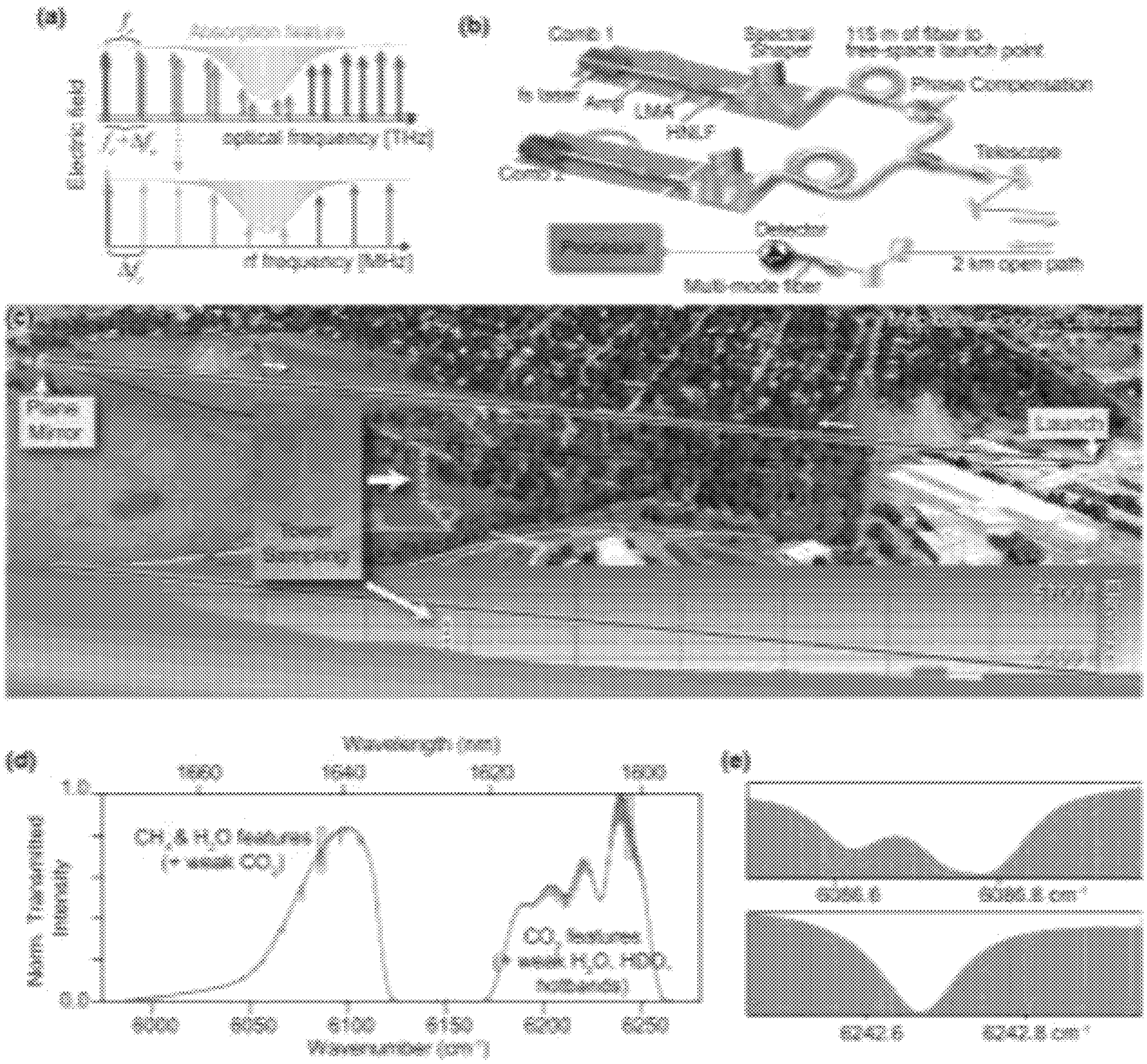

Figure [SEQ Figure * ARABIC]. Open-air path greenhouse gas sensing through dual-comb spectroscopy

Source: Rieker, G. B., et al. 2014 "Frequency-comb-based remote sensing of greenhouse gases over kilometer air paths," Optica 1, 290-298.

Open-air path greenhouse gas sensing through dual-comb spectroscopy. (a) DCS concept: two combs with slightly different tooth spacing interfere on a detector, giving a third rf comb with a one-to-one mapping to the optical comb teeth. (The actual experiment spans ~105 comb teeth.) (b) Experimental setup: two combs are amplified, pulse-compressed in large mode area (LMA) fiber, spectrally broadened in highly nonlinear fiber (HNLF), and filtered to generate light covering the spectral bands of interest. Two fibers carry the comb light to the rooftop, where the light is combined and launched in a ~40 mm beam (1/e2 diameter),and reflected from a 50 cm diameter plane mirror located 1 km distant. The return light is coupled to a multimode fiber and detected. The transmitted light power was limited to 1.5 mW so that the maximum received power was always below a conservative detector *nonlinearity threshold of 50 μW average power (500 fJ pulse energy). (c) Location of the 2 km interrogation path (red line, ground projection represented by black line), the tower with the point sensor intake (inset), and elevation of the beam path (bottom inset). (d) Example transmitted intensity showing the smoothly varying comb intensity and abrupt dips due to absorption. (e) Expanded view of absorption features. The typical gas absorption lines have ~40 teeth across each ~4 GHz wide line (top, several transitions from the 2v3 level of the CH4 tetradecad; bottom, R20 transition of the 30013←00001 band of CO2).*

Characteristics:

1. Primary Data Type: Range resolved concentration.
2. Result Type: Spatially resolved concentration (ppm) and emission rates using dispersion modelling using onboard meteorological data (temperature, pressure, humidity and wind speed).
3. Detection Range: Variable long path remote sensor
4. Specificity/Interference: High Selectivity, Ultra-High spectral (sub-nm) resolution and specificity of molecules.
5. Other Benefits. Can be made into an array with potential to detect: Simultaneous detection of other hydrocarbons, thus distinguish thermogenic or biogenic methane sources. greenhouse gases in the wide spectral range e.g. CO2, CO, N2O.
6. Measurement intermittency. Continuous
7. Measurement temporal resolution: Intermittency: Continuous.
8. Measurement Time: Depends on design, can be 1 – 100 minutes required precision- Scan rate of 1 MHz- 100 MHz (Time resolution ~ 1 μs) with 10 sec. averaging for 10 ppbv precision of methane.
9. Size. Small A few inches on a side.
10. Deployment Method. Sensors are relatively small and can be placed in a wide variety of locations, just need a place and means of affixing them.
11. Size: Breadboard prototype, fully automated.
12. Deployment Method: Fixed, fence line
13. Working Distance: ~ 100 m – 1 Km.
14. Environmental Limitation: None, temperature, humidity accounted in calibration.
15. Calibration Procedure: Reference Cell.
16. Maturity/TRL: Research/ few commercial instruments available.
17. Durability: Currently a research-based field instrument. Technology is still in research stage however there are commercial frequency comb spectrometers currently available at IRSweep Inc. ([HYPERLINK "http://www.irsweep.com"]).

Mode of Use: The technology is based on an electrically-pumped semiconductor laser that produces frequency comb integrated into a single few millimeters long laser diode and emits many highly stable wavelengths at the same time. DCS measurements are partially based on absorption spectroscopy where one frequency comb interacts with the sample, e.g. molecules in open air. The frequency and intensity of the transmitted light is No specific minimum working distance; max working distance determined by limit of detection.

4.2.2.9 Laser Absorption Spectroscopy Overview

Laser absorption spectroscopy (LAS) is a well-known technology developed over the last few decades for detection of methane and several other gases. The technique utilizes the wavelength-dependent absorption of laser light to quantify the concentration of any gas in a mixture. Furthermore, the amount of light depends on the specific gas, gas concentration, wavelength and total path length over which this light goes through the medium (air). There are several methods of magnifying the optical path length to improve the sensitivity of these sensors. This technique is extremely versatile and several variants of this technique have evolved over time. Typical wavelengths for methane are 1.6um and 3.3um. Tunable Diode Laser Absorption Spectroscopy (TDLAS) is a method of scanning the laser wavelength around the specific absorption line. This method significantly increases the signal to noise ratio and sensitivity.

The infographic below (Fig. 18) shows some common variants of LAS.

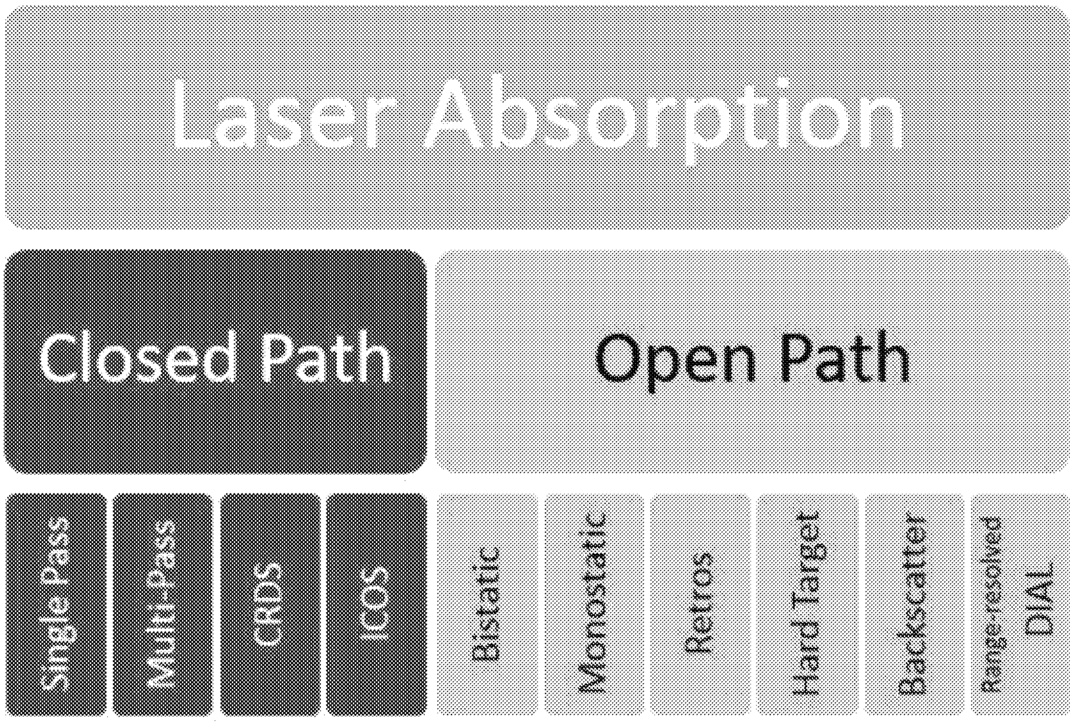

Figure [SEQ Figure * ARABIC]. Open and Closed Paths

Source: ITRC

4.2.2.10 Closed Path

Laser absorption closed path instruments measure gas over a fixed narrow path within a closed cylinder or bypass cell/tube. They have been proven to be much more precise and accurate than open paths. Closed path instruments are also able to measure gas in harsher environmental conditions such as high precipitation, and low visibility. Closed Path instruments include single-pass tunable laser absorption spectroscopy, multi-pass tunable laser absorption spectroscopy, cavity ring down spectroscopy, and integrated cavity output spectroscopy.

Single-Pass Tunable Laser Absorption Spectroscopy

Description:

This is the simplest mode configuration of a closed path laser absorption detection strategy. In this mode, the laser is directly transmitted through a medium gas sample cell and detected after light absorption a single pass. The light absorption is dependent on the concentration of the detected species. That is used to measure the concentration of methane, and path length of the sample cell.

Characteristics:

1. Primary Data Type: Path. Digital data signal
2. Result Type: Quantitative gas concentration.
3. Range (working distance): Variable, depends on the path length of absorption. Point measurement
4. Measurement Time: Up to kHz
5. Calibration Procedure: a. Using a calibration cell; b. calibration gas. Calibration-free operation possible
6. Maturity/TRL: Mature
7. Environmental limitations: Electronics are subject to environmental damage
8. Specificity/Interference: Design-specific; Interference can be avoided minimized from all other atmospheric interference by design choice.

Mode of use:

The implementation of this technology is very straightforward. The spectrum of methane /and spectral demultiplexing. The absorption depends on the path length "L" as shown in figure. The calibration process, if it is necessary, uses a static cell of known concentration methane.

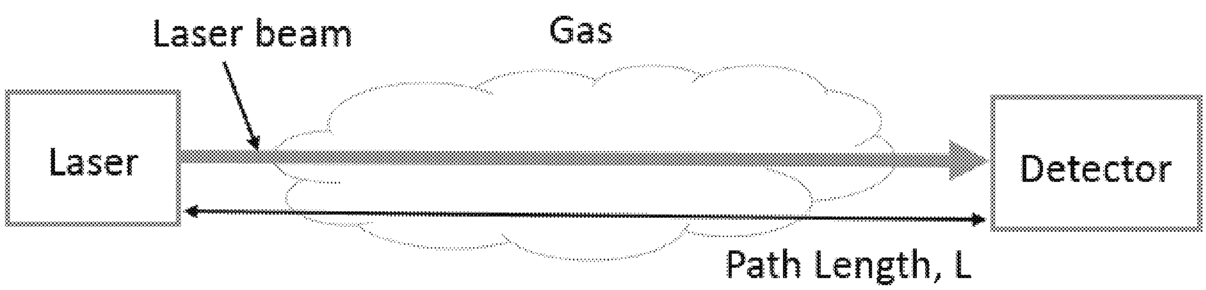

Figure [SEQ Figure * ARABIC]. Schematic for a basic tunable laser absorption spectroscopy setup

Source: Ritobrata Sur, Indrio Technologies

Multi-pass Tunable Laser Absorption Spectroscopy

In this method, path amplification is achieved by reflection between high reflectivity mirrors as well. However, the light travels a unique path between the input and output. This makes the sensors uniquely more robust than the other two cavity techniques. However, the path amplification achieved is lower. This leads to a reduced sensitivity depending on the path length.

Characteristics:

1. Primary Data Type: Point concentration
2. Result Type: Quantitative gas concentration
3. Range (working distance): Point measurement
4. Measurement Time: > 1 kHz
5. Calibration Procedure: calibration gas
6. Maturity/TRL: Mature
7. Environmental limitations: dust and vibration may reduce sensitivity
8. Specificity/Interference: Design-specific; Interference can be minimized from atmospheric interference by design choice.

Mode of use:

Similar to the other cavity techniques, the highest resolution spectrum can be achieved because of their insensitivity to laser-wavelength scan rates, enabling more precise inter-species spectral demultiplexing and data reduction schemes, such as wavelength modulation spectroscopy.

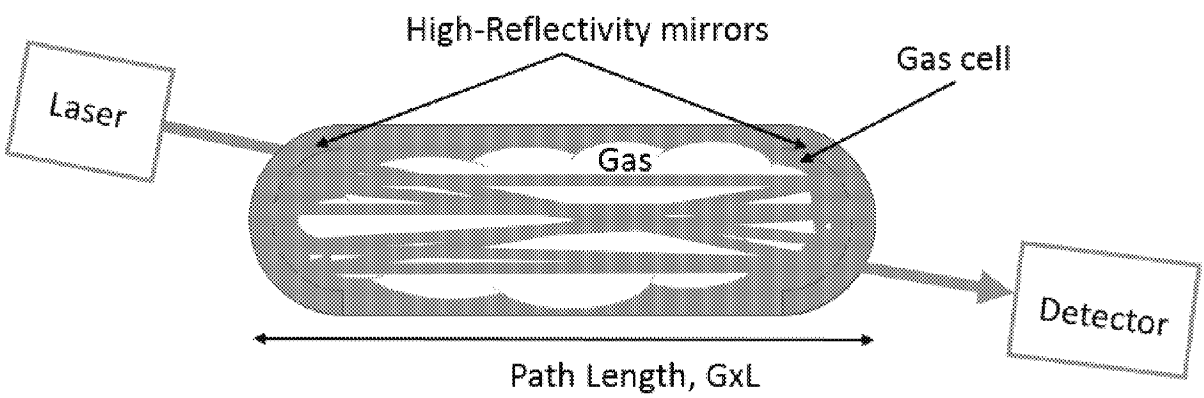

Figure [SEQ Figure * ARABIC]. Schematic for basic multi-pass tunable laser absorption spectroscopy

Source: Ritobrata Sur, Indrio Technologies

Cavity Ring Down Spectroscopy

Description:

Cavity Ring Down Spectroscopy (CRDS) is a variant where the significantly enhanced path of absorption is obtained by use of an optical setup consisting of two high reflectivity mirrors. The path enhancement is achieved by trapping the light between two mirrors until a certain level of desired path length amplification is obtained. The basic principle of operation is based on the fact that light bounces back and forth several times between the mirrors until the light is either absorbed or leaks through the high-reflectivity mirrors. The absorption in the cell is quantified from time-resolved "ring-down" signals in the optical cavity with and without the absorbing gas. This magnification factor is directly influenced by the reflectivity of the mirrors. This mirror is therefore prone to sensitivity to environmental factors that may alter the magnification factor.

Characteristics:

1. Primary Data Type: Point concentration. Digital data signal
2. Result type: Quantitative gas concentration
3. Range (working distance): Local Point measurement; no range
4. Measurement Time: ~ 1 Hz to 100 Hz
5. Calibration Procedure: By introduction of known concentration mixture in the cell calibration gas
6. Maturity/TRL: Mature
7. Environmental limitations: Detection sensitivity subject to environmental conditions
8. Specificity/Interference: Design-specific; Interference can be avoided minimize from all other atmospheric interference by design choice.

Mode of use:

A typical schematic for a CRDS setup is shown in Fig. 21. The high-reflectivity mirrors are used to amplify the detection sensitivity. The effective path of absorption for CRDS is effectively multiplied by a gain factor, G. This results in enhanced sensitivity of methane detection. Typically, an ultra-long path of a km can be achieved. This enables detection of sub-ppm sensitivity and also isotopic characterization, useful for source attribution.

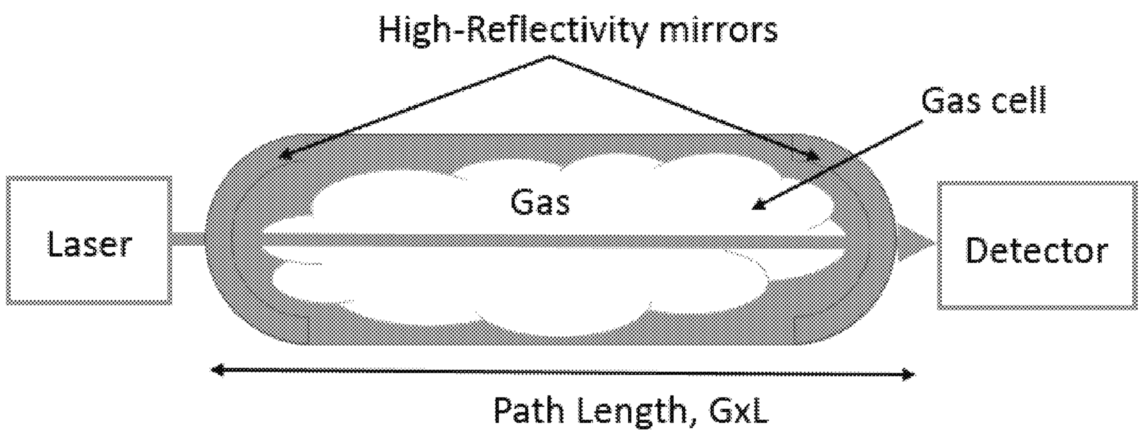

Figure [SEQ Figure * ARABIC]. Schematic for a basic CRDS setup

Source: Ritobrata Sur, Indrio Technologies

Integrated Cavity Output Spectroscopy (ICOS)

Integrated Cavity Output Spectroscopy (ICOS) is another path amplification technique with high-reflectivity mirrors with a more robust noise performance. Instead of using the cavity ring down time, the light is bounced back and forth between the high-reflectivity mirrors as a continuous stream and wavelength is scanned fast enough to avoid cavity resonance noise. This enables scanning of laser wavelength and can be used to resolve spectral shapes of methane and correct for interference to an extent that photons and laser wavelength is scanned fast enough to avoid cavity resonance noise. However, this technique is also susceptible to long term drifts and hence frequent calibration is required.

Characteristics:

1. Primary Data Type: Point Digital data signal
2. Result Type: Quantitative gas concentration
3. Range (working distance): Local Point measurement; no range
4. Measurement Time: ~ 1 Hz
5. Calibration Procedure: Calibration gas
6. Maturity/TRL: Mature
7. Environmental limitations: detection sensitivity is subject to environmental conditions
8. Specificity/Interference: Design-specific; Interference can be minimized from atmospheric interference by design choice.

Mode of use:

Very similar to the mode of operation as CRDS.

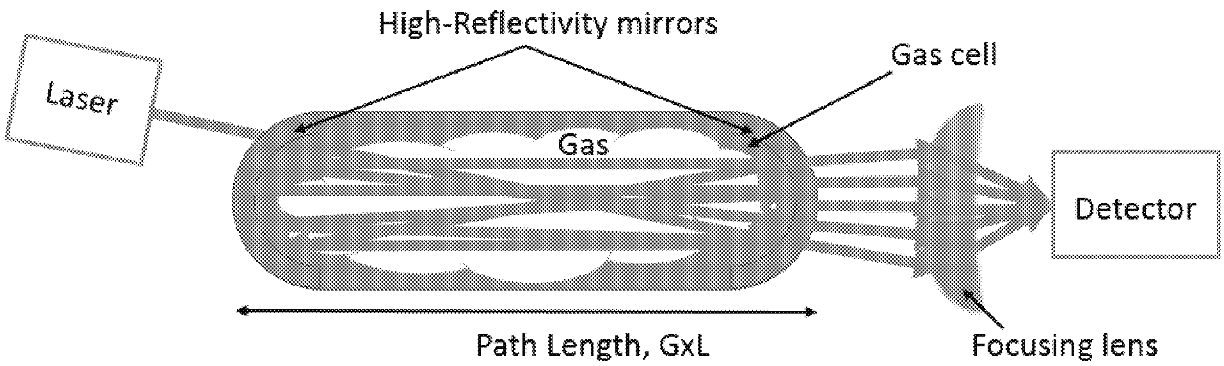

Figure [SEQ Figure * ARABIC]. Schematic for a basic ICOS setup

Source: Ritobrata Sur, Indrio Technologies

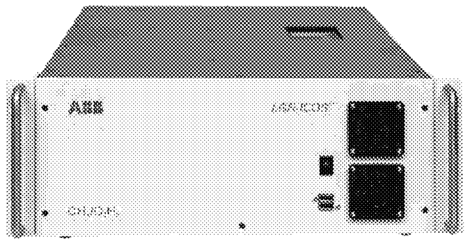

Figure [SEQ Figure * ARABIC]. ICOS system packaged for mobile leak survey

Source: ABB

4.2.2.11 Laser Absorption Spectroscopy - Open Paths

Open path tunable laser absorption spectroscopy techniques are based on the laser path being open to the atmosphere. The path can be either fixed in distance or variable depending on the instrument and mode of operation. This method has several advantages;

1. Fast response to highly variable gas plumes
2. Coverage of a large area
3. High sensitivity
4. Methane specific
5. There are several different methods deployed in open path systems as described below.

Bistatic

In a bistatic open path system, the laser is launched down range to a reflective surface; the reflected light is then angled to a separate receiver. The laser transmitter and receiver are located in two separate fixed locations. In theory, a laser fence can be set up around a facility. In this configuration, precise alignment and highly reflective mirrors (retro-reflectors) are used to obtain a long path length.

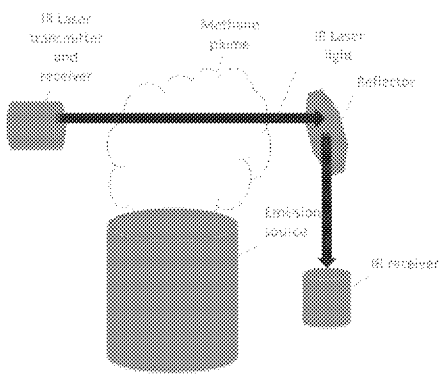

Figure [SEQ Figure * ARABIC]. In a bistatic configuration, the laser transmission and receiver are at located at two different locations. Often the laser is redirected by a reflector to create a boundary type path

Source: Heath Consulting

Monostatic

In a Monostatic open path system, the laser is launched down range to a reflective surface, the reflected light then returns to the launch position. The laser transmitter and receiver are located in the same fixed position. The effective path length is thus doubled resulting in increased sensitivity. Depending on the desired distance to cover, simple reflective surfaces to highly precise retro-reflectors are used. Monostatic systems are easier and more cost effective to deploy than Bistatic systems.

Monostatic designs can be either short paths or long paths. Short paths systems are useful for making point measurement. Long path systems are capable of detecting leaks which may occur along its path or to integrate the concentration of a large distance.

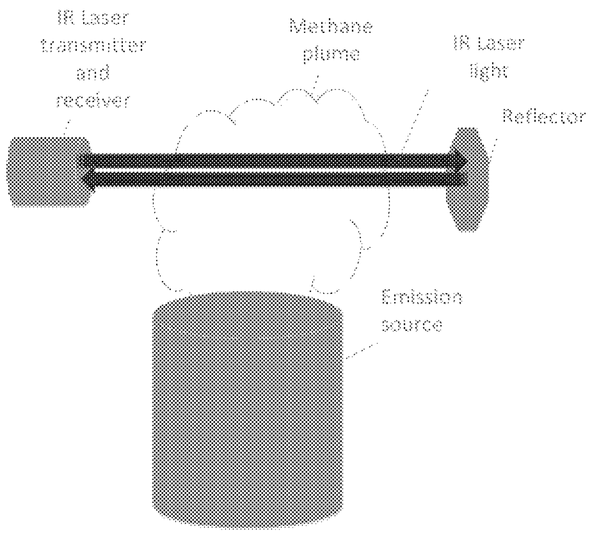

Figure [SEQ Figure * ARABIC]. In a monostatic configuration, the transmitter and receiver are co-located. The laser is reflected off a reflector back to the receiver

Source: Heath Consulting

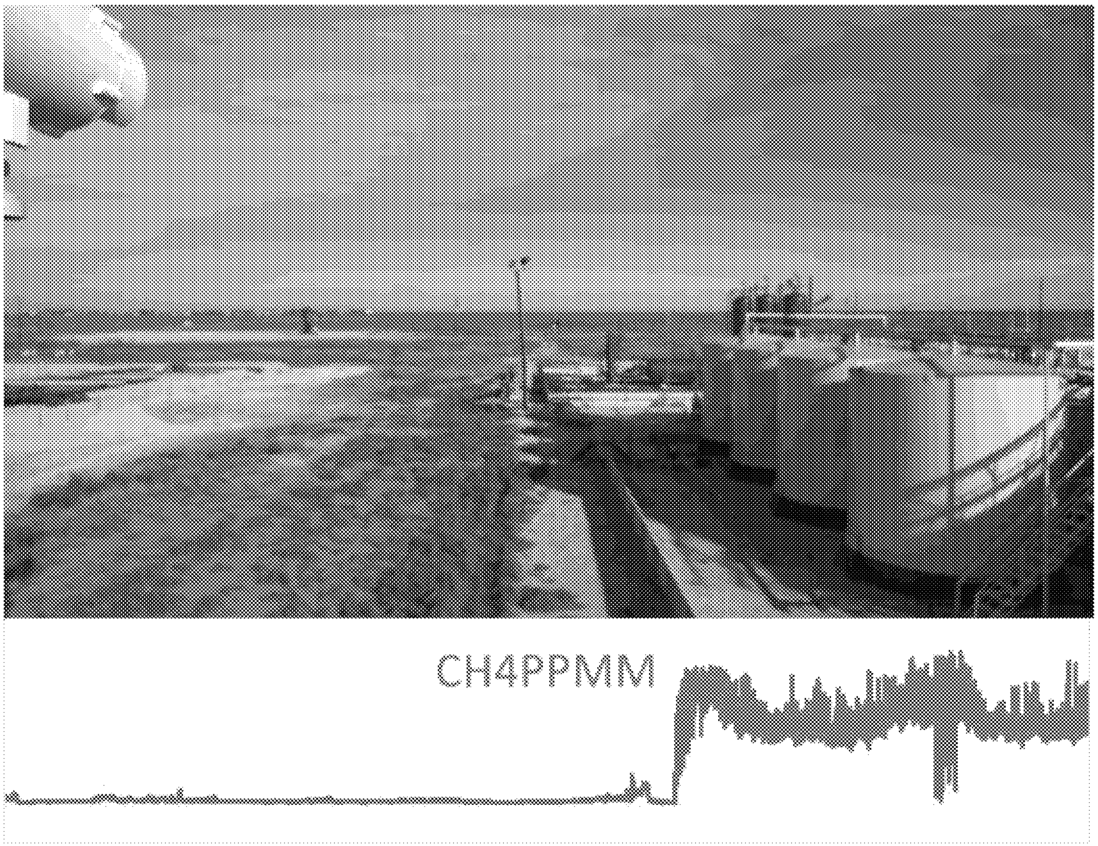

Figure [SEQ Figure * ARABIC]. Open path laser adjacent to an oil tank battery. Open thief hatch easily detected

Source: RMLD-REM, supplied by Heath Consultants

Backscatter

Backscatter is a special case of monostatic. The primary difference is that the natural background is used to reflect back the laser light. Backgrounds could be the ground, foliage, metal structure, etc. Natural backgrounds are not efficient reflectors, most of the light is scattered in all directions. Only a portion of the light is directed back to the receiver. As a result, the scanning distance is often much shorter than when using efficient reflectors.

Portable handheld instruments are based on the backscatter method. The advantage is the ability to scan an area or components rapidly.

Figure [SEQ Figure * ARABIC]. Portable handheld laser used for methane leak surveys and detections

Source: RMLD-IS, supplied by Heath Consultants

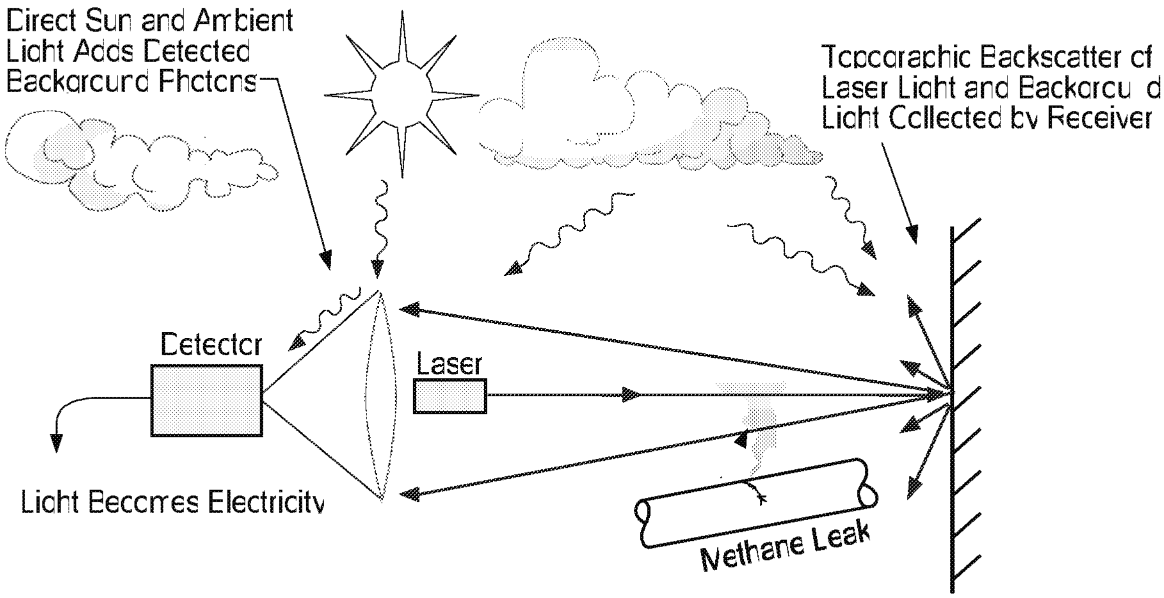

Figure [SEQ Figure * ARABIC]. Backscattering

Source: Heath Consulting

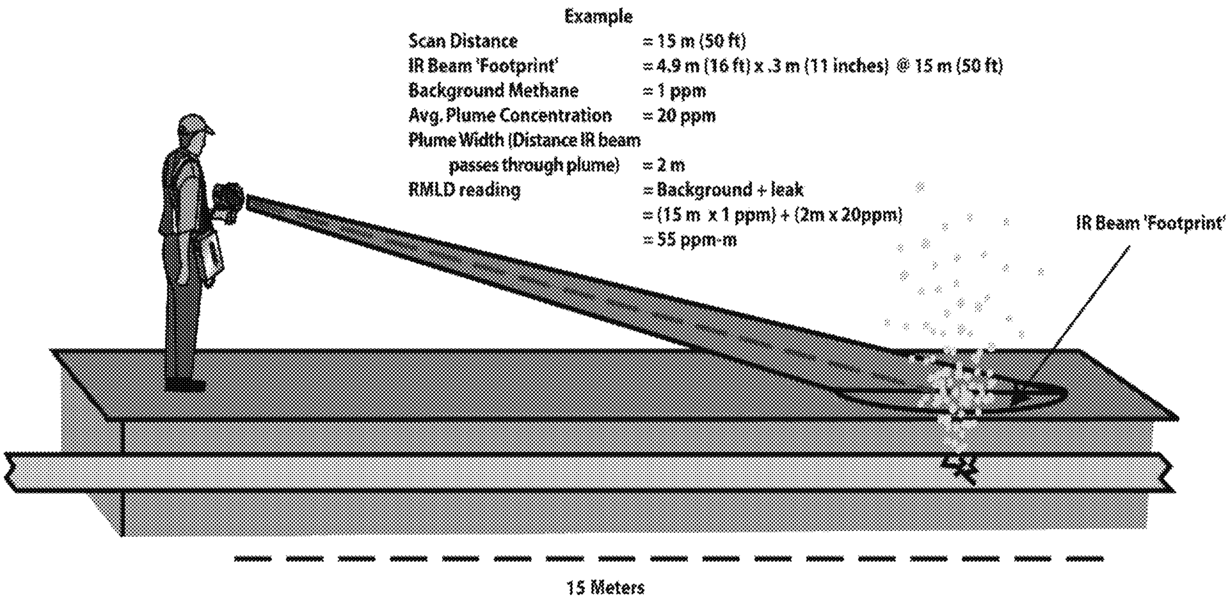

Figure [SEQ Figure * ARABIC]. Illustration of laser backscattering and leak detection using a scanning laser

Source: Heath Consulting

Range Resolved Differential Absorption Light Detection and Ranging (DIAL)

In this configuration, powerful lasers are used to provide a gradient concentration over the path length. The gradient is measured by reflecting two laser wavelengths off of aerosols and particles in the ambient air along its measurement path. The absorption wavelength is keyed to the compound of interest, while the off-absorption feature wavelength is used to measure the decay in strength of the absorption laser signal over distance. The range is resolved by a function of time. The measurement path is usually rotated in order to provide a complete map of the plume.

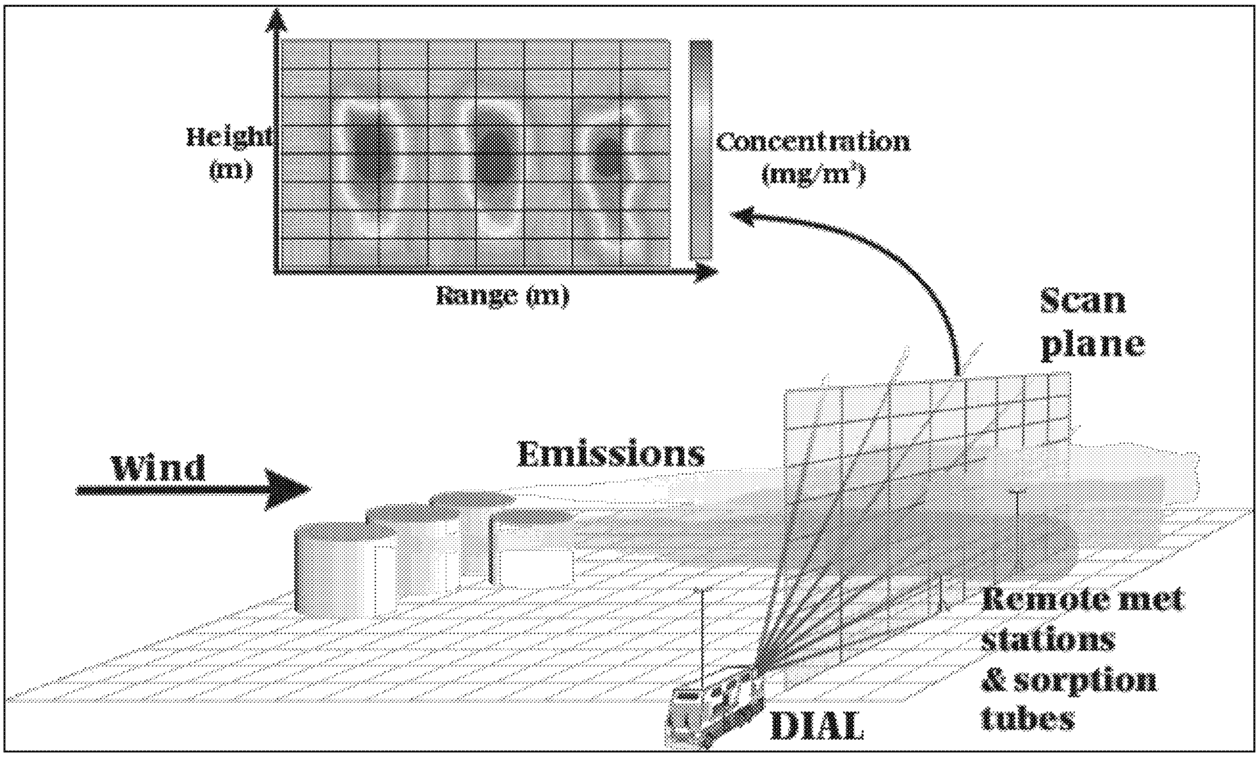

Figure [SEQ Figure * ARABIC]. The Differential Absorption Light Detection and Ranging (DIAL) Concept

Source: USEPA, http://slideplayer.com/slide/8331786/

4.2.2.12 Etalon

Description:

Etalon based gas sensors are based on the Fabry–Pérot effect of birefringence crystals in creating interference pattern. Through the use of Etalon crystals, specific interference patterns are created that match multiple absorption lines (signature) of the target gas. Matching multiple absorption lines increases the sensitivity and cross speciation rejection. Making Etalon based gas sensor highly selective to methane. Recent technology advances have enabled the development of low cost, low power detectors. Etalon based gas sensors are widely used by LDC's to conduct compliance leak surveys. Systems have been deployed that are mobile vehicle mounted and hand-held portables.

The optical system is composed of a high intensity light source (typically is broad in spectrum), optical band pass filters to reduce the light energy to the specific band of interest (3.3um for methane); polarizers, and photo detector. In order to alternate the birefringence pattern between the "on" gas spectrum and "off" spectrum a means to modulate the light is necessary. The modulation of the light spectrum significantly increases the sensitivity and rejection of interference gases.

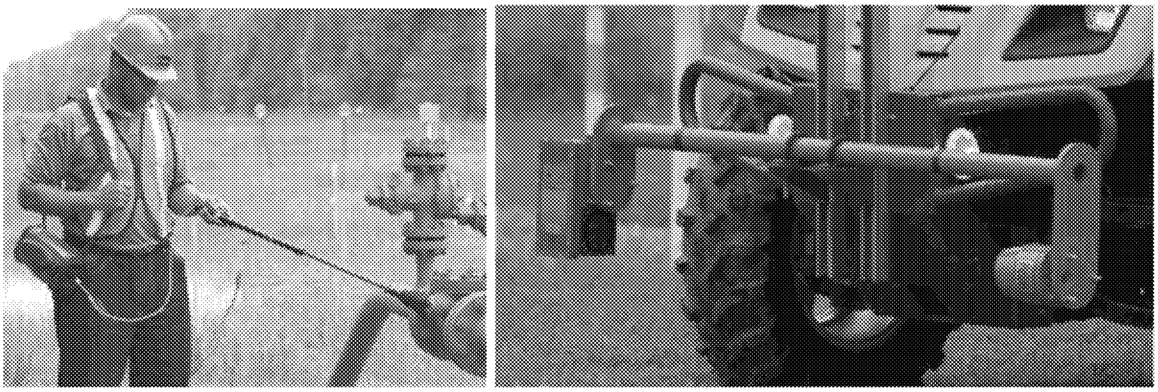

Figure [SEQ Figure * ARABIC]. Detecto-Pac IR (DP-IR) and Optical Methane Detector (OMD) are used to for methane leak detection

Source: Heath Consulting

Characteristics:

1. Primary Data Type: Path concentration
2. Result Type: Quantitative gas concentration
3. Detection Range: 0.2ppm to 2000ppm
4. Specificity/Interference: Highly specific; Interference can be minimized from atmospheric interference by design choice.
5. Other Benefits. Cost effective for the achieve level of sensitivity and speciation
6. Measurement intermittency. Continuous
7. Measurement temporal resolution: kHz
8. Size. From handheld to vehicle mounted
9. Deployment Method. Fixed, portable, mobile
10. Working Distance. Point measurement
11. Environmental Limitations. No specific limitations.
12. Calibration Procedure: built in calibration cell typical; operational temperature calibration is performed as needed.
13. Maturity/TRL: Mature
14. Durability, High durable. Systems deployed as early as the mid 90's are still in operational use.

Mode of use:

Open path; In this configuration, the light transmitter and receiver are positioned in a direct path open to the atmosphere. In a mobile application, the vehicle will drive through the gas plume causing the optical path to intersect the plume, giving a detection. In portable models, a probe is moved along the ground or along components drawing in a gas sample. As the gas passes through the sample cell, a gas detection results.

4.2.2.13 Optical Gas Imaging (OGI)

This section offers an overview of Optical Gas Imaging (OGI) technology for Methane gas detection. This section also provides accepted application of OGI technology for regulatory compliance initiatives and voluntary applications.

Optical Gas Imaging technology is a specialized infrared or thermal imaging camera developed to visualize gas leaks that cannot be seen by the naked eye. These cameras are comprised of an IR transmissive lens, an infrared responsive image sensor (the detector), a cooling system, a display screen or viewfinder and integrated electronics that provide capabilities for image processing, analytics, memory storage, wireless communication, just to name a few.

There are two types of approaches to optical gas imaging cameras that include, Active IR imaging and Passive IR imaging.

Passive IR imaging cameras use available ambient IR radiation to detect intensity differences between the ambient background IR and the gas plume radiation.

Active IR imaging uses an IR light source (infrared laser) that is projected toward the area of interest, reflected off a background and is absorbed or attenuated as it encounters a gas species along the optical path. The reflected attenuated infrared light signal is then captured by an infrared detector.

Passive IR Imaging

Mid Wave IR

For methane gas detection using OGI cameras, the commonly used infrared detector is a cooled Indium antimonide (InSB) midwave detector that operates in the 3-5 μm range and is integrated with a 3.2 - 3.4 μm bandpass spectral adaptation filter, specially designed for imaging methane and other hydrocarbon gases. It should be noted that OGI imaging cameras designed for wavelengths within this range may also detect other hydrocarbon gases as they exhibit absorption peaks within this range. OGI cameras are generally recognized not to have the capability to differentiate between various species of detectable hydrocarbon gases. It should be noted that there are variations of mid wave IR Optical Gas Imaging cameras that are designed for the detection of other specific gases such as carbon monoxide (4.52 – 4.67 μm) and carbon dioxide (4.2 – 4.4 μm). Additionally, OGI cameras can take various configurations that include handheld cameras, portable cameras using a mobile stand, and fixed installed cameras within a facility.

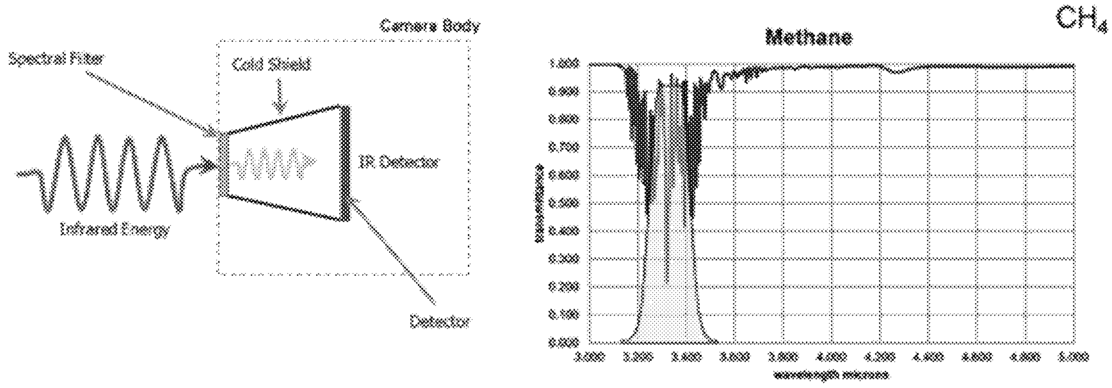

Figure [SEQ Figure * ARABIC]. Internal design of an optical gas imaging core and infrared absorption characteristics for methane

Source: FLIR Systems

Mid-wave Optical Gas Imagers detect methane and other hydrocarbons due to the molecules of these gases and how they absorb infrared radiation. When an OGI camera is pointed at a scene without a gas leak, all objects viewed will emit energy and reflect IR radiation through the lens and filter into the camera. The spectral adaptation filter will only allow certain wavelengths of radiation through to the detector to create an image. When a gas cloud exists between the objects being viewed and the camera and absorbs radiation in the filter's band pass, the amount of radiation passing through the cloud will be reduced if the amount of radiation leaving the cloud is not the same as the amount of radiation entering it.

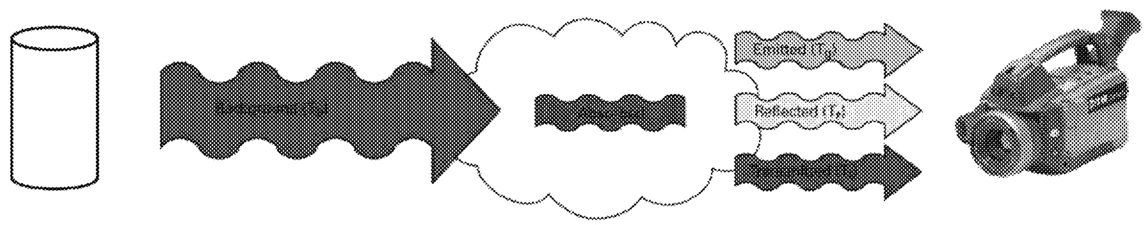

Figure [SEQ Figure * ARABIC]. Effect of a gas cloud absorbing radiation

Source: FLIR Systems

Applications

Optical gas imaging technology has been recognized, validated, and approved for use in meeting regulatory compliance reporting requirements by the EPA, BLM, and certain states. Additionally, the Oil & Gas Industry has found expanded use for optical gas imaging camera technology in applications related to leak troubleshooting, preventative maintenance, in taking various voluntary measures, and as a cost-effective solution providing savings to industry users. These applications for OGI technology along the O&G value chain are expansive starting with upstream operations (e.g., well-sites, compressor stations, gas plants), mid-stream (e.g., gathering/distribution, energy), downstream (e.g., refining, petro-chemical).

Mode of Use:

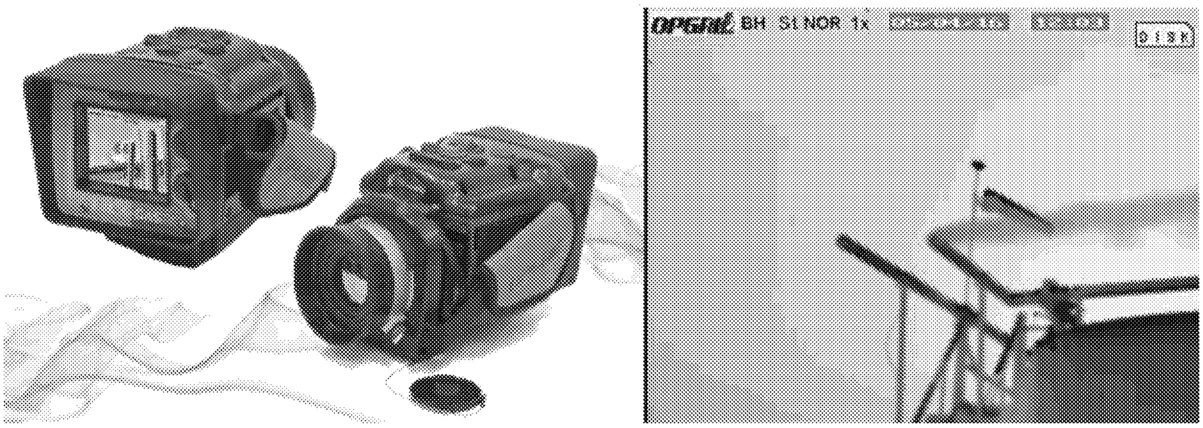

Figure [SEQ Figure * ARABIC]. Optical Gas Imaging Camera and image of a leak through a relief valve

Source: OPGAL EyeCGas, supplied by Heath Consultants

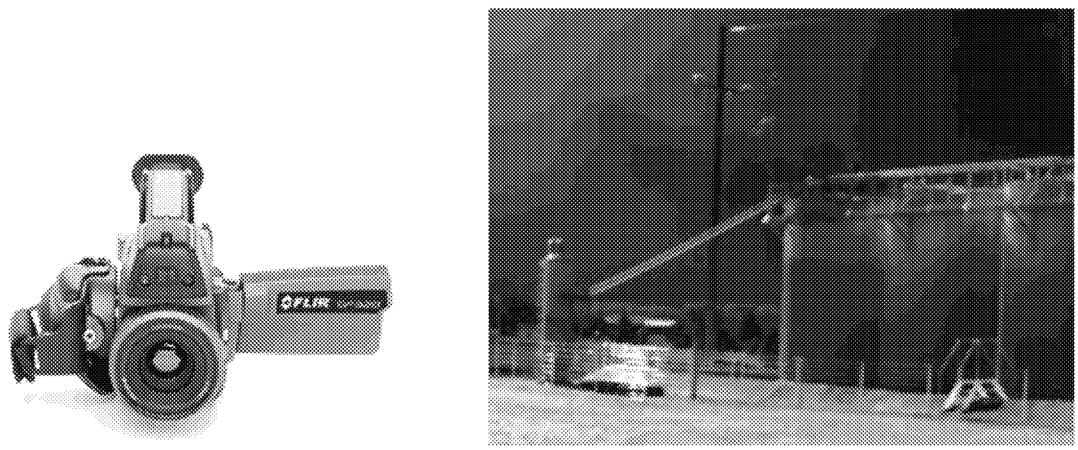

Figure [SEQ Figure * ARABIC]. Optical Gas Imaging Camera and image of a leak

Source: FLIR

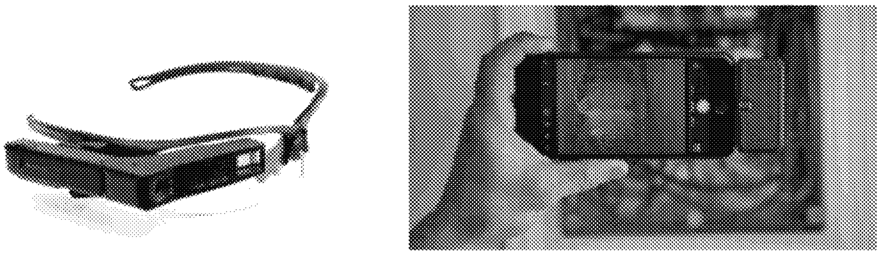

Figure [SEQ Figure * ARABIC]. FLIR Products

Source: FLIR [HYPERLINK "http://www.flir.com/FLIRNews"]

Quantitative Mid Wave IR

Quantitative Optical Gas Imaging (QOGI) is a technology in the Methane detection market that is a complimentary or add-on device to select mid-wave OGI cameras. QOGI consists of a tablet that connects to specific mid-wave OGI cameras via Universal Serial Bus (USB) and processes the data while connected to the OGI camera. These products allow the user to quantify leak rates in pounds per hour or liters per minute and quantify gases specific to the Response Factor of the gas. Methane is one of the 400 compounds that have been researched and can be quantified by a QOGI system.

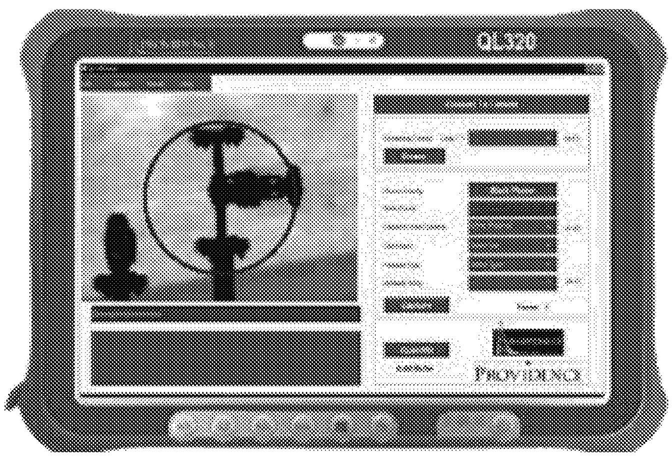

Figure [SEQ Figure * ARABIC]. A Quantitative OGI system

Source: Providence Photonics QL320™ / QL100™ [HYPERLINK "https://www.providencephotonics.com/"]

Long Wave IR

Methane also absorbs radiation in the longwave spectra from 7.3 – 8.2 μm. Many thermal imaging or Infrared cameras are longwave cameras but are not capable of detecting Methane and therefore not Optical Gas Imagers. Longwave cameras with filtering specific to Methane's absorption spectrum would be able to detect Methane. These cameras are currently not an approved regulator tool as compared to Midwave OGI which has been approved in some instances including the AWP for Method 21 and as the BSER for OOOOa.

Characteristics:

1. Primary Data Type: Focal Plane Array sensor with data filtered by spectral absorption
2. Result Type. Qualitative; Quantification by computational imaging techniques yet to be vetted
3. Detection Range:
4. Specificity/Interference: Environmental interference from fog, rain, snow.
5. Other Benefits.
6. Measurement intermittency.
7. Measurement temporal resolution: Adequate to support efficient LDAR activities
8. Size.
9. Deployment Method.
10. Working Distance. As close as allowed by procedural safety policies. Generally used at 15 feet to 50 feet.
11. Environmental Limitations.
12. Calibration Procedure: As required by EPA, state level regulations and per manufacturer requirements.
13. Maturity/TRL: Mature
14. Durability, Service Factors, and Calibration and Maintenance Requirements. Tool used to visualize the location and general severity of a leak

Measurement Temporal Resolution:

4.2.2.14 Fourier Transform Infrared (FTIR) Spectroscopy

Fourier Transform Infrared (FTIR) Spectroscopy is a technology capable of the measurement of multiple compounds (inorganic and organic) at once in real-time. The technique utilizes the wavelength-dependent absorption of infrared light to quantify the concentration of any gas in a mixture. Furthermore, the absorption of light depends on the total path length, concentration of the gas over which this light goes through the medium (air) and the absorption coefficient of the compound. The infographic below (Fig. 34) shows some common variants of FTIR.

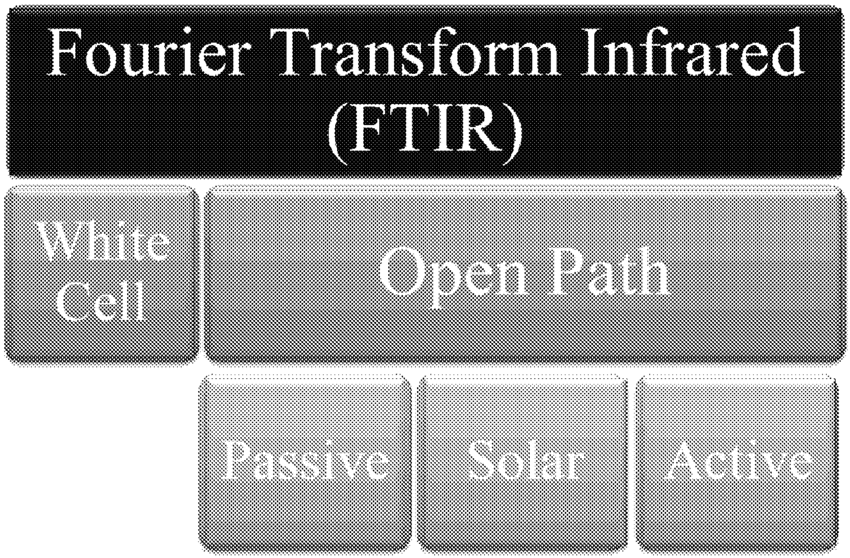

Figure [SEQ Figure * ARABIC]. FTIR Types

Source: ITRC

The basic principle of measurement uses an infrared radiation beam (generally 2.5 um to 15um wavelength) to interact with gas species in the gas which produce unique spectra patterns. The amount of the absorption can be correlated to the concentration and the path length of the interaction of the beam and the sample gas. The infrared beam is produced by an interferometer, which contains beam-splitter, laser, IR source and a set of moving and fixed mirrors. The purpose of the interferometer is to allow the measurement of all wavelengths at the same time. The fourier transform (mathematical algorithm) allows the interferogram signal (time/length domain) to be converted spectra (wavelength domain). The spectra are then used to identify and quantify the compounds in the sample gas using mathematical algorithms such as classical least squares and Beers-lambert Law, reference spectra, background spectra temperature, pressure, and path length. The path length, detectors (peak sensitivity, noise, cooling) and interferometers (spectral resolution) vary greatly depending on the need and target compounds. It should be noted that FTIR is capable of the measurement most volatile inorganic and organic compounds including isotopes (depending on concentration) and isomers with the exception of diatomic. The sensitivity of the measurements can be impaired due to large spectra interferents such as water and carbon dioxides or compounds with similar spectra fingerprints such as C4+ alkanes.

White Cell

In this mode of operation, the FTIR is used in a point monitor configuration. The instrument has the light source, interferometer, white cell and detector together. The sample gas is either pushed or pulled into the cell continuously or in static batches. The white cell serves as vessel to maintain the extracted sample gas at a consistent temperature and pressure, which is necessary for the use of reference spectra, and to allow the infrared radiation to be bounced multiple times through the gas in order to increase the path length for more sensitive measurements. White cells can either be a fixed or adjustable path length and are generally temperature controlled

1. Calibration Procedure: By introduction of known concentration mixture in the cell, dynamic spiking, calibration transfer standards with reference spectra
2. Maturity/TRL: Mature
3. Environmental limitations: Electronics and the detection sensitivity are subject to environmental conditions
4. Specificity/Interference: Design-specific; Interference can be mitigated with the proper analytical algorithms for most compounds.

Open Path

In this mode of operations, the FTIR is used in an open path format. This allows for infrared radiation beam to passed through the sample gas in the environment without need for sample extraction or conditioning. The Open Path FTIR instruments have several configurations such as passive, solar, monostatic and bi-static, which serve different purposes. Open path measurements generate a path averaged concentration over the path length of the measurement.

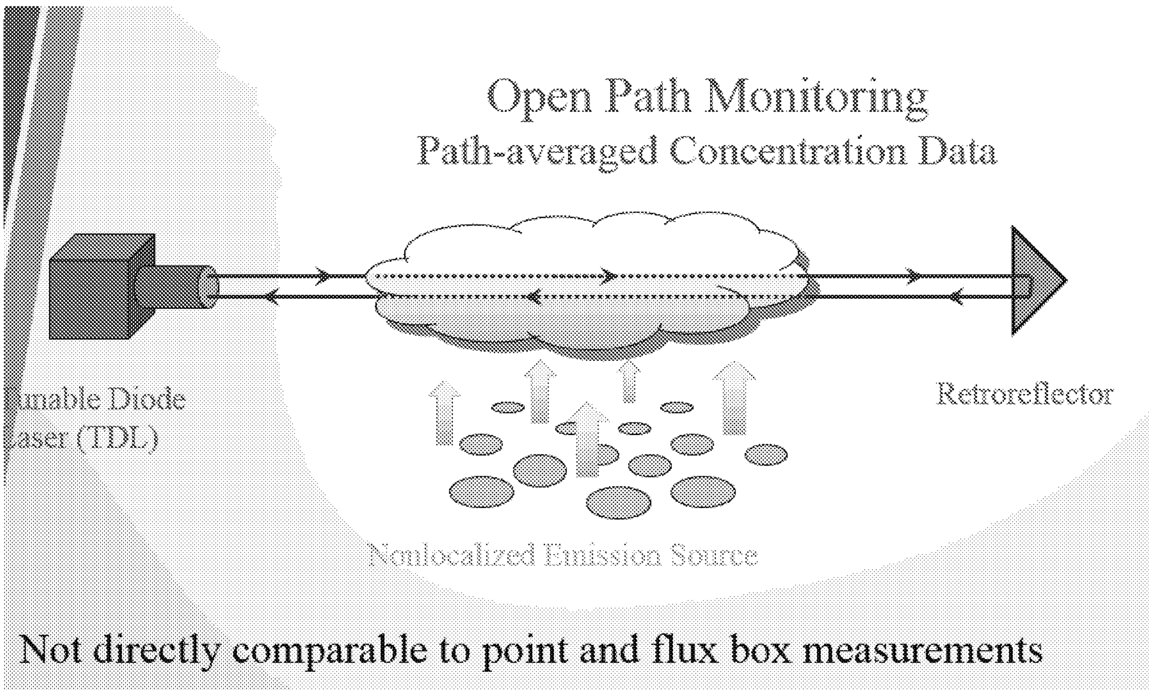

Figure [SEQ Figure * ARABIC]. Fourier Transformed Infrared

Source: FLIR

Passive (Monostatic). In this mode of operation, the FTIR uses an external elevated temperature source (a flame or combustion vent) to provide the infrared radiation. The elevated temperature gas compounds emit an infrared signature specific to their compound structure and temperature. This infrared radiation is then collected by the FTIR and analyzed. This technique must also account for the stray solar radiation and the compounds in the air between the elevated temperature source and the detector. The results from this technique are usually provided in a ratio of concentrations as the width of the plume is generally dynamic during measurements.

1. Specificity/Interference: Design-specific; Interference can be avoided from all atmospheric interference by design choice.
2. Environmental limitations: Electronics and the detection sensitivity are subject to environmental conditions significantly lower. This leads to a reduced sensitivity to absorption for the same methane absorption transitions.

Mode of use: Very similar to the mode of operation as CRDS.

Solar (Monostatic). Similar to the passive, the solar FTIR uses external infrared source, the sun, for the infrared radiation. The use of the sun as a source provides information on the total air column between the FTIR and the sun. Compounds at the ground level must be determined by the spectra shape changes due to temperature and pressure within the atmosphere. There are also techniques which use the Solar FTIR (Solar Occultation Flux) in a mobile format, which can provide a background level of compounds in the total air column to understand local contribution of a source or sources.

Characteristics:

1. Primary Data Type: Point concentration
2. Range (working distance): Local measurement; no range?
3. Measurement Time: ~ 0.1 to 10 Hz
4. Calibration Procedure: Various and architecture dependent – a) By introduction of known concentration mixture in the cell or b) Calibration-free mode. Not possible to do primary calibration due to large measurement path
5. Maturity: Mature
6. Maturity/TRL: Not sure the nomenclature – this is past research, but not at a fully commercial push button level
7. Environmental limitations: Only Electronics and the electronics detection sensitivity are subject to environmental conditions
8. Specificity/Interference: Design-specific; Interference can be avoided from all atmospheric interference by design choice.

4.2.2.15 Gas Filter Correlation Radiometry

Description: A GFCR instrument, or a Gas Filter Correlation Radiometer, is an opto-electrical sensor able to detect various gases present in the atmosphere, using a sample of the gas of interest as a spectral filter for identification. The sensor detector and optical systems are specifically tuned to narrow spectral ranges; only gases absorbent in the infrared region that is delimited by a narrow band pass filter can be detected. This limits perturbation by other molecular species and limits false alarms, resulting in very high precision and signal-to-noise ratio. It also eliminates the need for the complex spectral processing characteristic of hyperspectral imagers, generating low data rates and small transmission bandwidth. These traits make GFCR ideal for detecting methane via airborne or spaceborne microsatellite platforms. Figure 40 illustrates the gas correlation measurement principle.

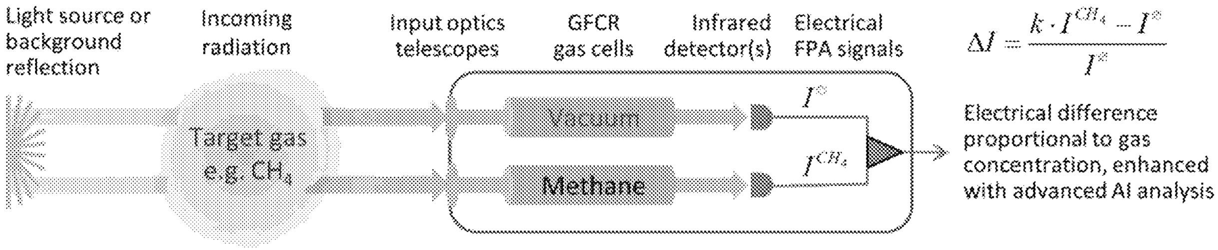

Figure [SEQ Figure * ARABIC] - Gas Filter Correlation Radiometry (GFCR) general operation concept

Source: Bluefield

Characteristics:

1. Primary Data Type: Quantitative integrated concentration-pathlength readings (in ppm-m)
2. Secondary data type (Result Type): Quantitative emission leak flow rates (in SCFH or kg/h) both in visual ground registered 2D maps.
3. Detection Range: < 1% natural abundance, 100 ppm-m integrated concentration, able to detect leaks 700 SCFH, 15 kg/hr. (single pass, 15 s stating time, 10 km/h ground winds). Accuracy is typically in the ±10-15% of reading.
4. Specificity: Focused only on one gas at a time. One gas detected per instrument/sensor. Main target is methane (CH4) but can also be tailored to other gases like CO2, SO2, NO2, N2O, etc..
   Provides ultra-high selectivity to the selected molecule, with low influence by other interferents
5. Other Benefits: More precise than hyperspectral spectrometers (for a specific gas) in a less complex (no moving parts) instrument at a lower cost. Insensitive to background and vibrations, immune to interferents, etc. The optically filtered approach does not require creation or analysis of spectra, contrary to the intense processing required by hyperspectral imagers.
6. Measurement intermittency: Continuous
7. Measurement temporal resolution: Processed data time resolution ≤ 15 s
8. Size: Backpack size instrument (Large)
9. Deployment Method: Airborne (airplanes & drones) & Spaceborne (microsatellite constellations)
10. Working Distance: Variable long path remote sensor (Depends on instrument and configuration). Airborne (aircraft or drone): Min working distance = 10 m, Max = 300 m (1000'). Spaceborne platforms: Low Earth Orbit (500–600 km)
11. Environmental Limitations: Sensor limited by dense cloud cover, impacting the frequency of geographic locations observable parameters, but the small pixel size allows probing through smaller clouds, increasing the probability of clear-sky scenes.
    SWIR operation mode requires sun illuminated scenes with relatively clear atmosphere (no-clouds to semi-cloudy conditions). (Spaceborne + Airborne platforms)
    MWIR requires $\Delta T > 5°$ (Airborne + ground vehicle platforms)
12. Calibration Procedure: Instruments are self-calibrated type on sensors for Quantitative Concentration measurements. Required sparse periodic ground reference ancillary calibration measurements (e.g. ground reference winds) for Quantitative Emission Rates measurements.
13. Maturity Technology Readiness Level: Development/evaluated, as GFCR technology has been used in a variety of airborne and space applications since the 1970s (including the HALOE gas

filter radiometer operated from 1991 to 2005 on NASA's Upper Atmosphere Research Satellite). Bluefield Technologies plans airborne demonstrations of a miniaturized GFCR for methane in 2018, followed by spaceborne demonstration in 2019.

14. Durability, Service Factors, and Calibration and Maintenance Requirements: GFCR radiometers are intrinsically stable, containing no moving parts or need to maintain stringent dimensional precision of an interferometer. As remote sensing solutions, they are intrinsically safe when used from a distance from the targeted scene.

Mode of use: GFCR is well-suited for trace gas measurement implementation on airplane/drones and microsatellites, as classical spectrometer technologies cannot reach the required size to be operated without substantial loss of performance, swath or spatial resolution. Bluefield Technologies is currently working to deploy GFCR sensors on microsatellites for the detection of methane emissions and ground leaks from space, which, combined with image processing AI, will provide accurate global coverage of every emitter on Earth with a very high frequency of measurements (monthly or daily, depending on the number of microsatellites).

4.2.3 Applications

Methane detection technologies can be used for a wide range of applications related to the mitigation of methane emissions starting at oil and gas production and processing sites and continuing all along the natural gas supply chain. Let us define here an "application" as the physical scenario for which we want to make the measurement, which describes the targeted types of emissions and the scale at which we are intending to detect the emissions. We can define the "platform" as the specific strategy, devices and specific deployment method we are using to make the methane emission measurement for the target application. An application reflects the user's desired goals, scale of application, accuracy and frequency of measurement, and assumptions about the distribution of emissions. The application selected depends upon the user's goals, which can be determined using these questions:

- What type of methane emissions are we trying to detect?
- How do the target emissions behave?

The answers to those questions then lead to follow on questions that determine the application:

- What do we need to determine about the emission source?
- When (with what frequency) do we want to inspect?
- At what scale are we applying the detection?

The platform will be the device used, the deployment method, and the processing required. The platform is the physical means by which a methane detection technology is deployed. The same technology may be deployed in different methods in some cases. Portable deployment methods are small and lightweight enough to be carried as handheld or backpack mounted devices. Vehicle-mounted technologies are transported by ground-based vehicles such as all-terrain vehicles or automobiles. Aerial deployments may be on fixed wing aircraft, helicopters, or unmanned aerial vehicles. Satellite-based deployments are possible for some measurement technologies. Stationary technologies are installed at fixed locations located at or near the areas being monitored. Many technologies can be deployed on several platforms depending on their size, weight, and power requirements.

What type of methane emissions are we trying to detect?

As was shown in Chapter 2 (Characterization of Emissions), emissions results from some very distinct and different sources along the natural gas supply chain.

The user might be focused on normal "fugitive emissions" that result from imperfect seals on sealed and packed surfaces, such as flange gaskets, screwed connections, closed valve seats (called "open ended lines"), valve stem packing, pressure relief valve seats, and compressor rod packing, and even pinhole leaks in pressure pipe. This narrow "fugitives" focus allows a variety of typical leak detection tools to be used.

The user may be focused on intentional vented emissions such as pneumatics devices, gas well liquid unloading blowdowns, equipment blowdowns for maintenance, and venting from tank flashing. Each of these may require unique measurement approaches if individual sources are measured.

The user might be focused only on unintentional emissions that result from maintenance issues or malfunctions, such as unlit flares/combustors, stuck dump valves on separators, and unintentional venting from a variety of sources. Many of these vented sources require more complex measurements, as many cannot be measured with typical leak detection tools. They also may require root cause analysis, in order to separate them from intentional and already reported and accounted for venting.

The user might even be focused on products of combustion from engines and heaters, where some unburned methane can exit in the exhaust.

Or the user may be focused on all of the above. Each of these answers will result in selection of different applications.

How do the target emissions behave?

The emissions from most simple fugitive sources are assumed to always leak once a leak starts. Therefore, a periodic emission measurement would catch most of the leaks occurring at a set point in time.

Some vented sources may behave this way also, but for some emissions from vented sources, the source may start and stop, such as pneumatic device emissions, tank flashing emissions, and blowdown emissions. A specialized measurement approach that can cover variable rates and can integrate enough time would be needed for these discontinuous emissions.

Emission studies continue to reveal that almost all emissions categories are known to have a highly skewed, non-normal distribution, with a minority of the sources contributing a majority of the emissions. Therefore, effective measurement requires an approach that can detect these few large important sources.

Once the user determines the answers to the above questions, they have determined their focus for measurement. Now they must ask these questions that can help determine the application and platform:

What do we need to determine about the emission source?

Do we need exact location? Do we need to quantify it? Do we need to just find and fix it? Do we need to separate out normal allowed emissions from abnormal unintentional emissions?

When (with what frequency) do we want to inspect?

If we have determined that the sources behave with unpredictable temporal variability, then we may need to have continuous measurement. Otherwise, a single measurement may suffice to find all the emissions that exist at a set point in time.

The temporal scale of an application denotes the time period of detection or quantification. An instantaneous scale such as a single OGI image provides a snapshot of emissions at the time of measurement. A discrete scale is a fixed interval that produces either a series of instantaneous readings or a time-averaged value. For example, some mobile monitoring approaches collect data for at least 15 minutes at each site before calculating an emission rate. Continuous scale refers to a technology that is permanently installed to monitor a location. Although continuous applications are designed to always collect data, environmental conditions such as wind direction may limit the value of the data to discrete intervals where conditions are appropriate for the detection.

At what scale are we applying the detection?

Are we measuring an entire basin, or a single site, or a single piece of equipment? This answer can set whether the device must closely examine each piece of equipment or would be applied only to know larger emissions from an entire site or combination of sites.

The spatial scale of an application refers to the size of the area or volume being targeted for detection or quantification. Some applications such as remote sensing quantify emissions at a scale larger than individual sites such as a basin or a satellite's spatial resolution. Although these applications have limited value for equipment level leak detection, they can identify areas of high emissions to prioritize finer scale surveys. Other applications identify the individual site where emissions occur, but do not resolve the exact location of the source. Finer scale surveys can localize the emission source to varying degrees of resolution from the approximate area of a site down to the exact component.

Applications can be described by general parameters such as their spatial scale, temporal scale, detection sensitivity, sampling efficiency, and platform. They also can be defined by their desired end results: application goals can include detecting fugitive emissions, precisely locating emission sources, quantifying their emission rate, speciating gases, or a combination of these aims. For each of these objectives, there are several methods for measuring and analyzing data that may be applicable under different sets of parameters and objectives. Understanding these applications is a critical step for designing and implementing evaluation programs.

The following sections give examples of application that meet particular methane measurement and mitigation goals that will drive the selection of a particular measurement device and platform.

4.2.3.1 Application: Fugitive Emission Sources at an Equipment Level

If the emission application is aimed only at fugitive emission sources, this is a subset of all sources at a site. Enhanced methane concentrations can be caused by onsite fugitive emission sources, onsite vented sources, offsite sources, and/or elevated methane background. For many Leak Detection and

Repair (LDAR) programs, only the fugitive emissions are targeted because of regulatory drivers and because on site fugitive sources represent unintentional emissions that may be repaired by the operator.

An application's primary goal can be to detect onsite fugitive sources without assessing their precise location or emission rates. Typically, this application is used to prioritize site visits for follow-up surveys with an application such as OGI that can pinpoint leaking components. Avoidance of false positives is critical for fugitive emission detection since mistakenly identifying an offsite or vented source as onsite fugitive can trigger unnecessary site visits.

For imaging technologies, distinguishing onsite fugitive emissions easily can be accomplished if emissions are detected from a source that should not have emissions when operating properly. Imagery can also identify abnormal emissions from vented sources, such as continuous emissions from an intermittent pneumatic controller, but a longer viewing period and knowledge of equipment operations may be required to confidently determine that emissions are not normal venting from operational equipment.

For applications that use methane concentration data, onsite fugitive sources can be distinguished from other sources by calculating values such as the approximate location, emission rate, temporal profile, or speciation of emissions. In general, this approach involves determining the baseline profile of offsite and onsite vented sources that can be encountered at the target site. Leak detection systems only indicate the presence of a leak when enhanced concentrations appear to originate from an onsite location not associated with a vented source. In practice, determination of fugitive sources can be highly complex and dependent on meteorological conditions. Methods for localizing sources and quantifying emission rates will be discussed in detail in the following sections. Only approximate estimates of these values may be needed for distinguishing onsite fugitive sources, but greater accuracy is required if fugitive and vented sources have similar locations or emission rates. The temporal profile of emissions can also be used to distinguish fugitive sources under some circumstances. For example, continuous methane concentration enhancement from an intermittent pneumatic controller may indicate a malfunction that causes abnormal emissions between actuations. Finally, speciation may provide useful information about the likely source of emissions. For example, a technology that measures carbon stable isotope ratios of methane can indicate if enhanced concentration is from biogenic sources such as landfills or cattle.

The following are historical methods for fugitive emissions detection: (move to history section up front Sect 4 – "These are 'long-standing' technologies that have been applied…."

Audio-Visual-Olfactory. The advantages of using audio, visual, and olfactory (AVO) for leak or source detection are that an individual is using tools readily available at all times, however there are disadvantages as well. AVO inspection uses human senses as a primary form of detection and identification. Audio involves listening for abnormal sounds associated with the process. Visual involves close inspection of components for cracks, deterioration, discoloration, obvious signs of wear etc. Olfactory uses sense of smell to identify areas of irregular or strong odors in the process area. The aforementioned detection methods can provide general leak detection but are limited in overall function. Limitations include training required, sensitivity to odors or odor threshold, and necessity for staffing to identify a leak. AVO is an important component of routine inspections, but there are limitations to using it as a sole method of identification.

Soap Bubble Identification can be used to identify a specific leak location. The soap bubble method is not practical to use in large scale leak surveys as it requires applying a soap bubble solution to a specific location to either confirm, or further narrow the identity of a leak. This technique does require direct access to the component. The soap bubble method is primarily used in conjunction with other methods for leak identification.

EPA Method 21 is used for the determination of volatile organic compound leaks from process equipment using a portable instrument which meets a specific performance criteria as specified within the method and applicable regulations and is appropriate for the target gas of the process (USEPA, 2017b). This method is intended to locate and classify leaks only and is not to be used as a direct measure of mass emission rate from individual sources. Generally, a calibration gas mixture of the target VOC is used to calibrate the instrument for both precision and accuracy of the target gas. An individual then inspects all components (piping, valves, flanges, pumps et.) of the process using the instrument to identify leak sources. Generally, at action level is used to determine what concentration is a leak requiring further mitigation steps. The method gives a quantifiable concentration to a leak source, but is not able provide emission rates, or specifically identify which VOCs are emitting from the leak.

4.2.3.2 Application of Optical Gas Imaging at Various Scales

Aerial Imaging. Several technologies exist which produce an image of methane emissions. In general, these technologies measure the effect of methane molecules on reflected light, either sunlight or light from an active source on the aircraft (typically a laser). By measuring the reduction of the light intensity, the amount of methane along a given path can be determined.

Images of these concentrations are produced either by collecting light in through an optical system, or by scanning a laser source across a scene. Depending on the spatial resolution of the system and the height of the platform, the images can then show the full geometry of a methane plume, allowing a source location to be determined. It is also possible to make source intensity estimates based on the concentration heat map and ancillary measurements or assumptions.

To date, none of these systems offer direct speciation. However, they produce concentration maps of plumes that usually indicate the source of the methane clearly.

Advantages: provides accurate locations of unknown sources, lower false positive rate, less expensive than sampling,

Disadvantages: lack of speciation, poorer minimum detection thresholds, less able to estimate overall emission rates of a large area.

Examples: (reflected solar): JPL HyTES, AVIRIS, Kairos, Synodon (laser-based): ITT ANGEL, Ball Aerospace Methane Monitor, LaSen

(Reference for OGI to USEPA, 2015a)?

4.2.3.3 Applications Requiring Quantified Emission Rates

There are applications that require more than simple detection of an emission and require actual rate quantification of an emission. Examples of such application needs are Emission Inventories, determining emission rates (or emission factors) for a particular source category, or applications that require proof of reduced emission rate by measurement.

There are a few options that produce emission rate estimates:

- Mass balance (aerial box models, larger scale)
- Downwind tracer flux (site scale)
- Direct flow measurement (individual source scale). This measurement from each source may be done by bagging, temporary flowstacks with meters, high-volume dilution sampling.
- Inverse dispersion modelling
- Computational fluid dynamics

Some of these methods are discussed in more detail below.

<u>High-volume dilution sampling</u> is a quantification approach that measures a component's emission rate by drawing in a source's total emissions with a known air flow. The high-flow dilution sampler (HiFlow) is a backpack sized portable instrument used to measure continuous leak emission rates of gaseous hydrocarbons such as methane. The device has been commercially available for 20 years and used in many studies and leak-detection-and-repair (LDAR) programs, especially in the natural gas supply chain (Fig 11). Unlike most other leak detection and screening analyzers that simply detect concentration of a species in air, the HiFlow produces a rate of emission measurement. Compared to other devices like flame ionization detectors and photo ionization detectors that simply measure concentration in a very small sample of air, the HiFlow instrument draws in a very large flow rate of air (between 5 and 10.5 cfm), with the result that the device can calculate and emission rate from the known air flow and the measured concentration. This approach assumes that the entire emission rate is captured by the HiFlow. This can be tested by allowing the device to pull in less air and check to see that it still calculates the same emission rate. The Hi Flow Sampler™ utilizes two sensors, a catalytic oxidation sensor for gas concentrations ranging from 0 to 5% by volume of methane, and a thermal conductivity sensor for gas streams containing higher methane concentrations. The internal computer switches between the two sensors at certain concentration levels. The leak rate measurement is conducted by placing the instrument hose inlet in a manner that captures the emission source being sampled, with the concept being that the instrument draws in enough excess air to capture the entire leak. The patent for the HiFlow has recently expired, and the manufacturer already announced a stop to production at the end of 2016. The device is still supported for three more years, both technically and for maintenance, by the manufacturer's agent, Health Consultants. The HiFlow has been in common use in national emission measurement studies as well as in leak-detection-and-repair programs, where it is often paired with a faster screening device such as an optical gas imaging camera. In recent years, a criticism of the HiFlow have been published (Howard, 2015), concerning conditions that may in certain circumstances, cause the device to read erroneously low. The manufacturer has published responses that state that proper maintenance and calibrations address all of these issues (Bacharach, 2015).

<u>Tracer flux correlation</u> approaches uses controlled release of a tracer gas at a known emission rate to estimate emissions of methane based on the assumption of equivalent dispersion (Roscioli et al, 2015; Mitchell et al, 2015). An ideal tracer can have its concentration precisely quantified with available equipment and has no other emission sources of the tracer near the target location. Common tracers

used at O&G sites include acetylene, nitrous oxide, and sulfur hexafluoride. (Note: Care should be taken in selecting a tracer as the tracers themselves can have environmental impact). Downwind of the tracer and target emission source, concentrations of both methane and the tracer gas are quantified along a crosswind gradient, typically by driving a vehicle-based platform perpendicular to the wind direction or using multiple open path instruments. If methane and the tracer have equivalent atmospheric dispersion, then both gases will have equal ratios between their integrated concentration enhancement and emission rate. Since the emission rate of the tracer is known, methane emissions are calculated by multiplying the integrated methane concentration enhancement by the tracer ratio. To test the assumption of equivalent dispersion, the dual tracer correlation technique releases a second tracer near the target emission source. If both tracers and the methane emission source are dispersed equivalently, then all three gases will have overlapping plumes with highly correlated concentration enhancement. If the target site has a large area with many potential emission source locations, then the dual tracer approach can provide information on the approximate location of the source by releasing the two tracers near different potential sources. At near downwind distances, the tracer plumes will be distinct with methane concentration enhancement most highly correlated with the tracer closest to its emission source. Increasing the downwind distance will cause the plumes to converge until all three gas concentrations are correlated. The tracer flux correlation approach is a highly accurate method for quantifying site emissions and has been used to assess other methodologies. Disadvantages include the need for onsite or fence line access for tracer release and downwind access for the mobile platform or open path instruments.

Other Test Method 33A (OTM33A) in an EPA mobile inspection approach that uses inverse point source Gaussian dispersion modeling to estimate site-level emissions (Brantley et al, 2014). A mobile platform with a high precision, fast response methane concentration analyzer and 3D sonic anemometer is positioned downwind of the target site. Methane concentrations are measured in tandem with wind speed, wind direction, and estimated atmospheric stability class. Based on the changes in methane concentration relative to variable wind direction, data are fitted to a Gaussian function to determine average peak methane concentration of the plume and then the source emission rate is calculated with a 2D Gaussian integration. OTM33A has the advantage of not requiring site access but the approach does require downwind access for the mobile platform. The method has an accuracy of of ±56% (Robertson et al, 2017) and may not be suitable in areas with rough topography or forested terrain where dispersion deviates substantially from Gaussian models.

Inverse Gaussian dispersion approaches use a mobile platform and inverse point source Gaussian dispersion to estimate site-level emissions. In contrast to OTM33A, which determines the horizontal concentration gradient of a plume during variable wind direction while the mobile platform is stationary, these approaches determines the horizontal concentration gradient by measuring methane concentrations while the platform is driving downwind of the site perpendicular to wind direction. Wind speed, wind direction, and atmospheric stability class are determined from either a platform-based anemometer or local meteorological station. There are two general methods for quantifying site emission rates with inverse Gaussian dispersion modeling. If the approximate source location is known, then the emission rate can be calculated by fitting the plume to a Gaussian model; since all other terms are known in the Gaussian dispersion equation, the emission rate can be back calculated from the concentration and meteorological data (Lan et al, 2015). If the location of the source is unknown, then the iterative forward dispersion modeling approach can be used to estimate the approximate source location and emission rate (Yacovitch et al, 2015). The method choses several potential source locations and uses forward Gaussian dispersion modeling to predict the shape of the plume encountered by the mobile platform (the shape of the plume is independent of the emission rate). Based on the fit of observed and predicted data, different source locations are modeled iteratively until there is an optimum fit with the observed data. The optimum source location then is used to estimate the emission rate using inverse Gaussian dispersion modeling. The first approach with a constrained source location has an uncertainty of approximately +184%/-87%, but the second approach has higher uncertainty of approximately ±300% due to the indeterminate source location.

Inverse dispersion modeling approaches use the relationship of concentration enhancement and meteorological conditions to approximate the location of a source and potentially mass rate. A simple approach is to evaluate the relative variability of the methane enhancement and wind direction. If a source has a short upwind distance from a sensor, then the methane enhancement will change rapidly with changing wind direction. At greater distances, this change will be less temporally pronounced since the plume has greater horizontal dispersion before reaching the sensor. Relatively small changes in methane enhancement during variable wind conditions indicate that the source of the methane enhancement likely is offsite or due to elevated regional background concentrations. A more complex approach is to calculate downwind and crosswind distance between a source and sensor with inverse Gaussian dispersion modeling. This requires either variable wind direction or a moving sensor to characterize the horizontal profile of a plume. If the plume is assumed to fit a Gaussian distribution, then iterative optimization can be used to determine which downwind and crosswind distances result in the best fit between observed and modeled concentrations (Yacovitch et al, 2015). This approach requires highly accurate meteorological data since other parameters such as wind direction and atmospheric stability class affect plume dispersion. Spatial uncertainty greatly increases at shorter distances since other factors such as turbulent mixing from equipment downwash can cause plumes to deviate substantially from Gaussian dispersion.

Mobile flux plane approaches use a mobile platform to quantify site emissions by profiling the horizontal and vertical profile of a plume (Rella et al, 2015). The mobile platform has a high precision, fast response time methane analyzer and a vertical sampling mast with six different sampling inlet ports. The vehicle is driven downwind of the site perpendicular to wind direction to measure horizontal methane enhancement of the plume. Vertical methane enhancement of the plume is measured by using a gas storage manifold that allows a single analyzer to measure methane enhancement from all six sampling inlets. The site emission rate is calculated by multiplying wind speed by methane enhancement integrated over both the horizontal and vertical direction. If the plume cross section is not fully captured by the transect, then a trapezoidal approximation approach can be used to model the missing portion of the plume. The mobile flux plane approach has a precision of +63%/-70%.

Atmospheric mass balance is an aerial approach that relies on the principle of conservation of mass to quantify emissions from an area bounded by upwind and downwind transects (Karion et al, 2013; Petron et al, 2014; Karion et al, 2015; Lavoie et al, 2015; Conley et al, 2016). The general approach is to use an aerial platform to measure methane concentrations along an upwind and downwind transect within the atmospheric boundary layer and then integrate methane concentrations horizontally across the transect and vertically from the ground to the top of the boundary later. The methane emission rate from the area bounded by the transects is calculated as the difference in the upwind and downwind integrated methane concentrations multiplied by mean horizontal wind speed and the cosine of flight transect perpendicular to the horizontal wind direction. A variation of the approach omits the upwind transect and relies on the edges of the downwind transect to estimate background methane concentrations. Another variation uses a spiral flight path around the target area to more accurately assess upwind and downwind concentration differences across the vertical gradient. Depending on the length of the flight paths, atmospheric mass balance can be used to estimate emissions from a basin, individual site, or any size area in between. A successful mass balance measurement requires a steady wind speed and direction, constant boundary layer height, and no mass transfer across the boundary layer. Uncertainty depends on meteorological conditions and variability in background methane concentrations, but generally is in the range of ±30–50%.

Quantitative Optical Gas Imaging (QOGI) is a new technology for identifying methane gas leaks and estimating their severity. Compared to traditional techniques, QOGI allows for the rapid areal screening of a facility to identify the potential gas leaks.

QOGI uses infrared optical imaging tuned to a narrow spectral band of approximately 3.2-3.4 micrometer (μm) wavelengths, which makes it specialized for detecting the spectral absorption characteristics of most carbon-hydrogen (C-H) bonds. As leaks occur in natural gas pipelines, the pressurized methane is released to the atmosphere resulting in significant adiabatic cooling. This significant temperature drop leads to a localized temperature gradient which is visualized using the QOGI technology. Also, even if there is no adiabatic cooling and the methane has the same temperature as ambient air, methane will still be detectable if the apparent temperature of the background is different from the ambient temperature. After identifying the leak detection threshold of the detection equipment, thermal imaging cameras estimate the size and concentration of the leaked gas plume. QOGI is based on a signal extracted from the gas plume using certain plume extraction algorithm, and calibration curves that are established empirically between this signal and known leak rates under certain conditions. This allows the QOGI device to examine movement and density of the plume and to then estimate an emission rate.

4.2.3.4 Applications Requiring Speciation

At sites where multiple gases may be released, one of the goals of an approach may be related to speciation including identifying gas composition, detecting or quantifying only a subset of specific gases such as methane, or separately assessing individual gases. Some technologies, particularly sensors utilizing narrow-band absorption, only respond to methane. Other technologies such as passive IR OGI respond to multiple hydrocarbons and cannot distinguish methane from other gases such as ethane. For technologies that can respond to and distinguish among multiple gases, two general approaches are used: spectroscopy and mass spectrometry. Spectroscopy relies on the unique electromagnetic radiation absorption spectra of individual gases; this can involve measuring individual absorption bans that differ between commonly occurring gases or a hyperspectral approach that compares the full spectra. Mass spectrometry identifies gases by comparing their mass-charge ratio (m/z). Since many gases have similar m/z, mass spectrometry may be coupled with a separation technique such as gas chromatography to first separate gases based on their molecular properties. Unlike spectroscopy, which can work remotely by measuring absorbed or reflected light, mass spectrometry requires the gas to physically enter the detector.

4.2.4 Summary

Numerous, diverse technologies are currently available or in development for methane leak detection. Most of these technologies either produce an image gas or measure point or path methane concentrations. These data are used in a variety of applications including the detection, localization, and quantification of fugitive emission sources at oil and gas sites. The suitability of individual technologies for particular approaches is dependent on their performance on key metrics such as detection limit and response time. This chapter has summarized the state of knowledge at the time of writing to help stakeholders understand the variety of existing technologies. Due to the rapid advancements in this field, details such as commercial availability, cost, and detection limit likely will be outdated. Stakeholders should consult the most recent data and references to assure that information on individual technologies is accurate and up-to-date, including the availability of new technologies developed after the completion of this document.

5 EVALUATION OF METHODOLOGIES

In response to growing interest and growth in innovative leak detection systems, there has been concurrent development of approaches for evaluating the performance of these systems. The evaluation of leak detection systems should be based on an objective assessment of technology-neutral, quantitative metrics directly related to stakeholder goals. As discussed in Chapter 4, there are numerous sensor technologies and applications that can be used to detect, locate, and/or quantify methane emissions, including stationary arrays or point sensors, moving point or line sensors, box flux estimation, plume imaging, long path sensing, and tiered approaches integrating multiple systems. Depending on the target sites and stakeholder goals, several of these approaches may be able to successfully meet primary performance criteria even though they differ in other metrics such as methane concentration detection limit. This chapter will provide examples of past and ongoing programs for assessing innovative leak detection systems. Although it is beyond the scope of this document to provide detailed protocols for evaluating the full diversity of technologies and applications, adhering to these principles will help stakeholders design and implement protocols for assessing the ability of systems to meet desired goals.

5.1 Defining System Objectives and Metrics

The next few sections will illustrate and define initial system objectives and metrics.

5.1.1 Clarify system objectives

Successful evaluation of leak detection systems is dependent on a clear understanding of the desired goals of the system. Prior to designing an evaluation protocol, stakeholders should agree on the system's primary objectives. Ideally, the objectives should be agnostic to system technology and platform to expand the number and type of potentially successful systems. The following list of questions and example answers can help guide the definition of system objectives. This list is not intended to be exhaustive but provides a starting point for stakeholders.

5.1.2 What is the ultimate objective of the leak detection system?

The most important question for stakeholders to address is the primary goals that they hope to achieve by implementing leak detection systems. Examples include:

- Detect methane concentration above a specific concentration limit or difference from baseline concentration
- Detect the presence of emission sources above a specific emission rate
- Quantify the emission rate of a site and/or individual sources
- Locate fugitive emission sources at a site/sub-site level to increase the efficiency of follow-up, component-level surveys such as OGI
- Locate fugitive emission sources at a spatial resolution allowing direct identification of the leaking component

- Assess if emission reductions achieve a percentage target
- Assess if emission reductions are equivalent to another technology
- Achieve compliance with a specific regulation or voluntary program

5.1.2.1 What is the typical size and complexity of target sites?

Will use of the system be limited to upstream or midstream facilities? Is it intended for small, relatively simple sites such as single well pads or large, complex sites such as processing plants? Do these sites have access to grid power and/or communications infrastructure such as cellular towers? Example O&G facility types are listed below. Although this document is limited to oil and gas facilities, many of the same principles would apply to evaluating methane detection systems at other types of sites.

- New, multi-well production sites
- Well pads of any size or age
- Gathering compressor stations
- Processing plants
- A field of upstream and midstream oil and gas sites
- Gathering pipelines

5.1.2.2 What is the spatial distribution of target sites?

- Many leak detection systems work at different temporal and spatial scales – some are more suited to finding small leaks at a single facility, while others are intended to quickly find high emission rate sites over a large area. The relative value of these approaches depends on the spatial distribution of the target sites.
- Single facility
- Cluster of closely-spaced sites
- Widespread, loosely distributed sites
- Linear (e.g., pipeline leaks)

5.1.2.3 What environmental and meteorological challenges apply?

After deciding in which regions the system will be used, one must determine what environmental and meteorological conditions may cause challenges for leak detection systems. For example, some sensors may fail or have decreased accuracy if ambient temperature falls outside an optimal range. Systems that rely on atmospheric dispersion modeling may perform poorly if high wind speed, complex structure, or rough topography causes dispersion to deviate from Gaussian assumptions. Offsite methane sources such as landfills can complicate the ability of systems to determine when elevated concentrations indicate onsite emissions.

- Minimum and maximum temperature
- Typical wind speed and direction
- Topography
- Vegetation structure (e.g., forested or grassland)
- Extreme weather (e.g., blizzards, dust storms)
- Other local methane sources (e.g., landfills, cattle)

5.1.2.4 Who will maintain the equipment and how often are site visits required?

Systems vary in their required level of maintenance. Determine who will visit sites to maintain equipment and how often sites can be cost-effectively visited.

- Will the site operator, regulator, or a third party maintain the equipment?
- For systems located permanently at a site, do system objectives include a maximum frequency of site visits for maintenance or related activities such as instrument calibration?

5.1.2.5 Who will receive data from the system and what are their requirements?

There are many possible approaches for handling data from leak detection systems, such as sending data to operators who record information for later regulatory review, or direct monitoring by regulators. Stakeholders should determine if they have specific data requirements such as a minimum reporting frequency indicating the presence or absence of leaks. They should also carefully assess what data quality issues most affect the primary objectives. For example, a system with a primary objective of identifying large leaks for follows up surveys likely will fail objectives if a high number of false positives triggers frequent inspection of low emission sites.

- Will the site operator, regulator, or a third party receive data from the systems?
- How frequently does data need to be received?
- What communication infrastructure is required to transmit data?
- What is the tolerance towards false positives, false negatives, or other inaccurate data?

5.1.2.6 Does the system need to be specific to methane and/or measure other compounds?

Oil and gas emissions are comprised of a mixture of hydrocarbon including methane, ethane, and volatile organic compounds (VOCs). Does the leak detection system objective refer specifically to methane or other species such as natural gas, VOCs, or total hydrocarbons? If the composition of emissions at target sites has low variability, then measuring one compound may be a suitable surrogate for estimating other compounds. If the objective includes distinguishing emission sources with distinct composition (e.g., natural gas vs. landfill or produced gas vs. tank flashing), then measuring multiple hydrocarbon compounds or the stable isotopic composition of methane may be used to determine the source of emissions.

- Natural gas
- Methane only
- Isotopically-distinct methane (13C:12C or 2H:1H ratio).
- Total hydrocarbons
- Volatile organic compounds
- Speciate individual compounds

5.1.2.7 What secondary objectives are mandatory for successful system performance?

In addition to the primary objective, determine if there are any criteria that must be met for the system to be considered successful. For example, a successful system may be required to meet a cost per site limit if it will be considered suitable for widespread deployment. Many of these criteria may be interrelated. For example, the cost per facility of leak detection systems depends on both the temporal and spatial scales of detection (Fig. 41).

5.1.2.8 Are there any regulatory requirements or barriers?

Are there any federal, state/provincial, or local regulations that mandate or prohibit specific performance criteria or technologies for the system? For example, regulatory requirements to measure both methane and VOC emissions may rule out the use of sensors that are specific to methane. A regulation may also establish specific performance criteria for alternative technologies, such as the NSPS OOOOa Alternative Means of Emissions Limitation, which requires systems to achieve equivalent or better annual emission reductions as semi-annual OGI. In these cases, meeting the regulatory requirement may be considered the primary objective of the system.

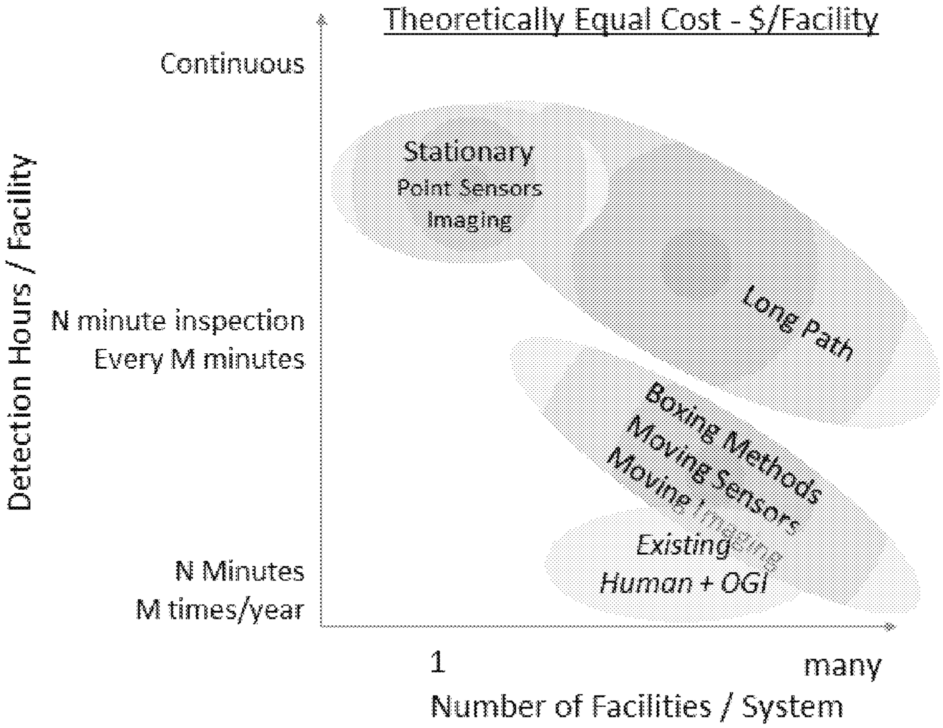

Figure [SEQ Figure * ARABIC]. The cost per facility of leak detection systems depends on both the temporal and spatial scales of detection

Source: Dan Zimmerle, Colorado State University

5.1.3 Categorize system objectives

After addressing stakeholder questions, categorizing the primary objective of the leak detection system can guide the design of an evaluation protocol. Most objectives can be classified into one of three categories related to the performance defining metric units: concentration, emission source, or emission reductions. A fourth category, equivalency, is discussed separately but typically can be considered as special examples of the first three categories.

1. *Concentration*

   The system objective is to assess the value or rate of change of methane concentration (or related pollutants like VOC). This is the simplest category of system objectives since performance is independent of meteorology or dispersion assumptions that affect the relationship of concentration and emission rates.

2. *Emission source*

   The system objective is to detect, locate, and/or quantify individual emission sources (or aggregate site-level emissions). This category is more complex because emission rate detection limits typically are highly sensitive to variable environmental parameters such as wind speed. Additionally, systems may depend on assumptions such as Gaussian dispersion that are violated in some field conditions. This category does not require knowledge about the distribution or behavior of sources in the target site population since performance can be defined at the individual source level.

3. *Emission reductions*

The system objective is to reduce emissions a certain percentage, magnitude, or equivalent amount as another technology. In addition to the issues related to emission sources, this category has the additional complexity of requiring knowledge about the distribution and behavior of emission sources. For example, if a system can detect emission sources above a set emission rate, then site leak rate distributions are needed to calculate what percentage of total emissions would be detected by the system. Since site leak profiles can be highly variable, evaluation of this category may require modeling to calculate the probability of achieving different levels of emission reductions at individual or groups of sites.

4. *Equivalency*

Regulations sometimes mandate the use of a specific technology for environmental compliance. In order to promote innovation, these regulations may include a process for permitting the use of alternative technologies. Typically, operators or technology developers are required to submit data that prove the alternative technology is equivalent or better than the default technology at achieving target metrics such as detecting leaks of a certain emission rate or reducing site-level emissions. Equivalency determinations can be classified into two groups: 1) equivalent assessment of individual emission sources, and 2) equivalent reduction of aggregate emissions.

For the first group, which can be included in the concentration or emission source category, an alternative technology must demonstrate equivalent detection, quantification, or localization of individual emission sources of a similar type, concentration, emission rate, and/or gas composition. An example of this type of equivalency is the EPA New Source Performance Standard OOOOa definition of OGI (40 CFR §60.5397a(c)(7)(i)(B)), which specifies that OGI equipment "must be capable of imaging a gas that is half methane, half propane at a concentration of 10,000 ppm at a flow rate of ≤60g/hr from a quarter inch diameter orifice" (USEPA, 2015a). This determination is an assessment of a technology's ability to detect emissions from a well-defined source that can be evaluated with a controlled release under laboratory or field conditions.

For the second category, an alternative technology must demonstrate equivalent emission reductions at a specific spatiotemporal scale such as a site's annual emissions. This is a much more complex determination because a technology's minimum detection limit and response time affect its ability to reduce emissions (Figure 42). Since many sites have highly skewed emission rate distributions, a technology that quickly detects large emission sources may lead to more reductions than a technology that slowly detects all emission sources. An example of this approach used a Monte Carlo approach to simulate component emissions at a processing plant and assessed resulting emission reductions from the Method 21 and OGI (Epperson et al, 2007). The model demonstrated that OGI resulted in equivalent or better site-level emission reductions due to its ability to more quickly detect and mitigate large emitters than the current work practice of Method 21. In response, EPA revised their regulations to allow use of OGI as an alternative work practice to Method 21.

EPA NSPS OOOOa requires OGI to be used for leak detection and repair at oil and gas well pads (semi-annually) and compressor stations (quarterly). The rule includes a provision for other technologies to be used as an alternative means of emissions limitation (AMEL) if they achieve at least equivalent emission reductions of GHG and VOC emissions as OGI. The AMEL application process is outlined in 40 CFR §60.5398a with several submission requirements including a description of the technology and procedure and 12 months of data demonstrating equivalent reductions at the affected facility (USEPA, 2015b). Currently, the regulatory language includes ambiguity and EPA has not yet provided guidance on the specific data or procedures necessary for a successful application. Outstanding questions include the definition of an affected facility and the use of modeling versus empirical data.

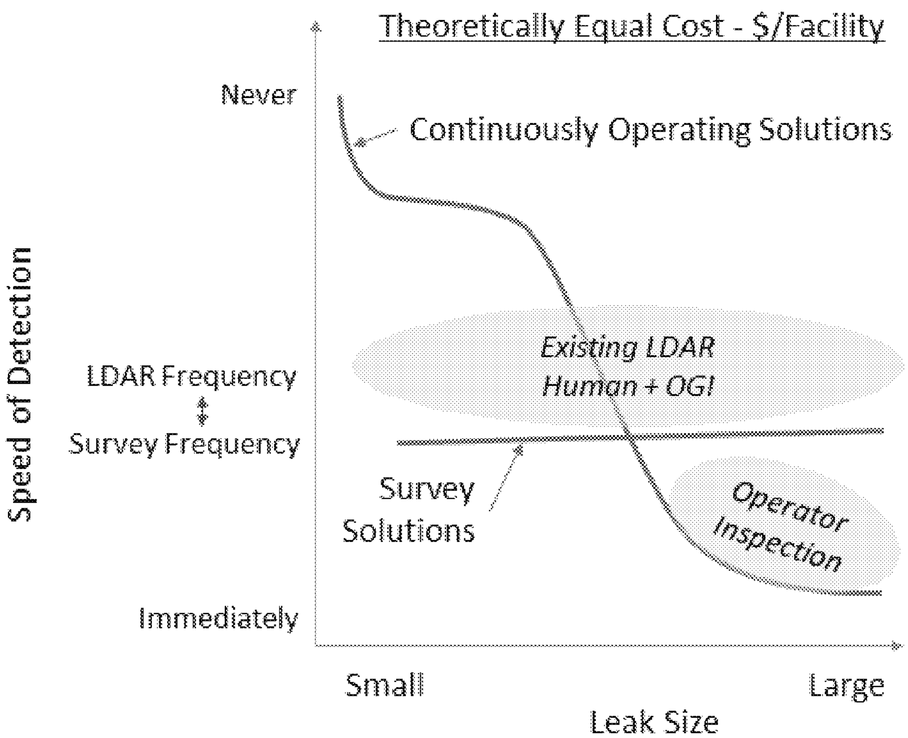

Figure [SEQ Figure * ARABIC]. Potential emission reductions are dependent on the relationship of the detection limit and response time of detection systems

Source: Dan Zimmerle, Colorado State University

5.1.4 Express system objectives as testable metrics

Once stakeholders have clarified and categorized the system objective, the next step is to express the objective as a quantifiable, testable metric that describes the primary goals, target sites, and acceptable limitations of the system. The statement should include sufficient detail so that any system that agrees with the full statement is considered compliant with the objectives. Three example objective statements are listed below.

1. *Concentration*. The system will signal when fence line methane concentrations exceed 10 ppm CH_4. The system must have a 95% probability of signaling within 4 hours of elevated concentration during precipitation-free conditions of -20 to 120 ^{0}F and <10 mph wind speed.

2. *Emission source*. The system will detect, locate, and quantify emission sources at well pads in North Dakota. Emission sources ≥ 6 scfh must be located within 1 meter spatial accuracy and their emission rate quantified to ±30% within 24 hours. Sources should be identified as intentional, unintentional, or offsite with less than a 5% error of misclassifying intentional or offsite sources as onsite, unintentional. The system must perform successfully 80% of the annual hours with a maximum of 1 week to detect emissions.

3. *Emission reductions*. The system will achieve equivalent or better emission reductions at gathering stations than quarterly OGI following NSPS OOOOa work practices. Equivalency is defined as percent of annual emission mitigated at the company/basin-level. In addition to the system's ability to detect leaks, it must be evaluated as part of a work practice that includes the emissions threshold and time to repair detected leaks.

5.2 Designing evaluation protocols

Following the expression of system objectives as a statement with testable metrics, stakeholders should consider potential evaluation protocols for assessing these metrics. Each category has a different set of general approaches that can be used to evaluate systems objectives:

1. *Concentration*

    a. Laboratory testing

    For objectives related to measuring concentration, systems can be tested under controlled laboratory conditions to assess performance criteria such as minimum detection limit, precision, response time, interference from other compounds, and the effect of conditions such as temperature and humidity. Laboratory testing has the advantage of being relatively low cost and better able to test defined conditions such as specific ambient temperature.

    b. Field trial

    Although laboratory testing is well suited for assessing concentration-based goals, it may be insufficient for assessing system performance under challenging conditions such as snow and dust storms that are difficult to replicate in the laboratory. Additionally, field testing can be used to assess the robustness of a system to long term exposure to outdoor conditions.

c. Example: Methane Detectors Challenge [Link to Case Study Summary in Appendix]

d. Example: EPA NSPS OOOOa OGI definition [Link to Regulatory Summary in Appendix].

2. *Emission sources*

a. Laboratory testing

Emission source-based objectives are difficult to assess in the laboratory because most leak detection systems rely on complex analyses of concentration and meteorological data to detect, quantify, and/or locate emissions. It is possible to perform controlled releases in a laboratory setting, but satisfactory performance under controlled conditions does not indicate that the system will succeed under sub-optimal conditions. Due to the difficulty in replicating complex, diverse atmospheric conditions, laboratory testing is insufficient for assessing how a system will perform in the field.

Laboratory testing may be useful for screening systems with emission source objectives when there are limited resources for follow up field testing. In particular, early stage technologies that are unable to meet concentration-based metrics will likely have issues quantifying emission rates. Initial screening can be used to eliminate any systems that do not meet underlying concentration metrics, but care should be taken that the metrics are not arbitrary and allow for innovative approaches to analyze low quality data.

b. Field-based controlled releases

Controlled releases under field conditions are ideal for systems with emission source objectives because they can assess the accuracy of source quantification and/or localization under realistic meteorological conditions. Ideally, field testing should use controlled releases that are of similar emission rates and release points as targeted sources. Long-term testing at field sites allows controlled releases to be tested under a diversity of meteorological conditions. Performing multiple controlled releases under each set of conditions can be used to calculate the probability of detection as a function of emission rates and other relevant conditions such as wind speed.

Ravikumar et al 2018 evaluated OGI with controlled single blind leak detection tests at the METEC site to determine probability of detection curves based on emission rate and distance. They determined that FLIR-based OGI detection limits are an order of magnitude higher than previous estimates, but sufficient to achieve maximum reductions as part of a period leak detection and repair program.

c. Field trial

Compared to field-based controlled releases, a field trial at oil and gas facilities has the advantage of incorporating realistic conditions including the human element of leak detection and repair into the evaluation process. Field trials can include controlled releases by intentionally releasing emissions from oil and gas equipment.

d. Example: CSU METEC [Link to Case Study Summary in Appendix]

3. *Emission Reductions*

a. Field-based controlled releases and field trials

For emission reduction objectives, field-based controlled releases and field trials can be used to determine probability of detection functions. Although this data are not sufficient for assessing emission reductions, an accurate understanding of the probability of detection is necessary for estimating emission reductions.

b. Modeling

Computer modeling is highly valuable for evaluating emission reduction objectives due to the probabilistic nature of emission rates (Figure 43). Several studies have demonstrated that O&G sites have highly skewed emission rate distributions with the top 5% of sites responsible for about 50% of total emissions. These high emission sites, sometimes known as superemitters, may have malfunctions or abnormal process conditions that can be mitigated to reduce emissions. The occurrence of superemitters is primarily stochastic and therefore frequent monitoring is needed to identify these sites. Due to the skewed distribution rate, an application that quickly detects high emitters may achieve greater emission reductions at the population level than an application with a lower detection limit and slower response time. However, at the individual site level, a high emission screening approach (with poorer minimum detection thresholds) could result in lower emission reductions at the majority of sites with relatively low emissions, but much greater reductions at high emission sites. Therefore, the demonstration of equivalent reductions is complicated by the variability in site emission rates if "affected facility" must be interpreted as a single site such as a well pad. Alternatively, an affected facility could be defined as an aggregation of individual sites such as all of an operator's well pads in a basin. Another approach could be to define an affected facility as a probabilistic model site, which uses the emission rate distribution of a population sites to represent a single site with a probability distribution function of emission rates. This approach would allow emission reductions to be calculated as probability function with a successful determination of equivalency based on a metric such as a $\geq$95% probability of equal or greater emission reductions than the reference approach.

The efficacy of many applications for leak detection, quantification, and localization is impacted by meteorological conditions and site configurations. This includes the emission reduction potential of OGI, which physics-based modeling has shown to be dependent on parameters such as view distance and emissivity, some of which are not defined in OOOOa leak detection protocols. The immense diversity of conditions under which an application can be implemented precludes an empirical evaluation of all possible scenarios. Computer-based modeling, coupled with empirical validation of model accuracy, is a potential solution to rigorously evaluate application efficacy under the most likely encountered meteorological and site conditions. There are several recent examples of modeling used to evaluate sensor performance. A Gaussian dispersion model used 10 years of local, hourly meteorological data to predict the median hours to detection of potential emission sources at three model sites with different layouts of point and open-path methane analyzers (Kemp et al, 2016). The FEAST model is a virtual gas field simulator that predicts emission reductions of various leak detection and repair programs. An effective demonstration of equivalency could include an empirical evaluation of an application at a structurally complex site such as a gathering compressor station over a time period such as 12 months that assesses performance under a wide range of meteorological conditions. If a computer model can accurately predict the detection limit and response time for different sources as a function of environmental parameters, then a probabilistic model can be used to simulate the performance at other sites. This approach could allow a scientifically rigorous determination of equivalency while minimizing the number of sites required for field testing.

[FEAST MODEL [Link to Case Study Summary in Appendix] [Kemp et al, 2016]

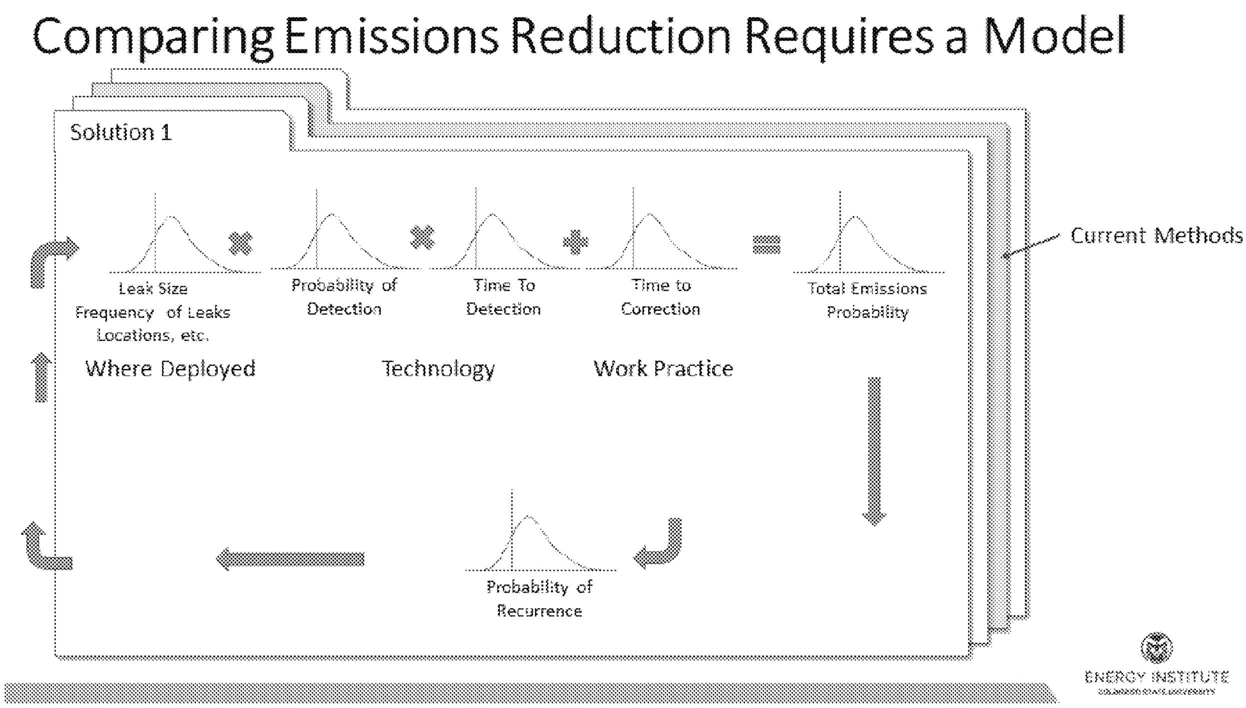

Figure [SEQ Figure * ARABIC]. System objectives based on emission reductions requires a model incorporating the probability and time to detection with data on leak populations and repair protocols

Source: Dan Zimmerle, Colorado State University

c. <u>Side-by-Side Testing</u>

Controlled Statistical Field Survey Method

The intention of the Controlled Statistical Field Survey method testing is to conduct sufficient system level performance testing of the technology to confirm that the system in whole meets the requirements of the end user, regulations and market place. It specifically compares the performance of one technology against another technology, typically a technology that is generally accepted practice.

This survey method is intended to establish the performance characteristics of a new method or technology against established Method 21 or OGI leak survey methods.

Terms and Definitions:

Minimal Detectable Leak (MDL): A leak with environmental conditions or gas plume characteristics that an instrument has 50% probability of detecting when used in normal operation mode.

Minimal Actionable Leak (MAL): A large enough leak which meets specific guidelines, levels or conditions which require it to be repaired.

Non-detectable Leak: A leak with environmental conditions or gas plume characteristics that the instrument is not able to detect.

Technology Under Test (TUT): A new technology that is being tested to determine if it meets performance requirements:

Baseline Technology (BT): An existing technology that is already in use, generally accepted and validated for use in the application

Single Blind Survey: A leak survey conducted using actual known leaks. The TUT is blind to where the known leaks are. Known leaks were acquired by previous surveys and have not been repaired.

Double Blind Survey: A leak survey conducted without a-prior knowledge of leak locations. Both the TUT and BT survey independently of each other but within time and distance constraints.

The Controlled Statistical Field Survey testing is to ensure that the TUT meets the requirements of the intended use and user requirements. The Blind Survey validation method compares statistical leak detection performance of the TUT to the performance of the Baseline Technology (BT) under actual field conditions. Single Blind and Double-blind methods are used to collect independent data samples which aid in identifying performance differences based on the technology and operator use of the technology.

Characteristics that need to be profiled include items such as the practical minimal detection ability, survey technique, statistical comparison, unit-to-unit repeatability, and user-to-user repeatability.

The following statistical data will be derived:

1. Overall detection statistics. A minimum of 100 leaks, Single blind Survey method. Determine the following statistical values for both the TUT:

a. % Leaks Found

b. % Missed Leaks

c. % Leaks not detectable

d. % False alarms

2. Overall detection statistics. A minimum of 100 leaks, Double blind Survey method. Determine the following statistical values for both the TUT and BT:

a. % Leaks Found

b. % Missed Leaks

c. % Leaks not detectable

d. % False alarms

3. Minimal Detectable Leak Characterization. A minimum of 50 leaks. Determine the environmental conditions, distance from leak, leak plume volume, leak plume gas concentration that creates a probably of 50% or less of detecting the leak. Determine the following statistical values for both the TUT and BT:

a. Gas plume concentration

b. Variability of gas release (constant, intermittent)

c. Conditions which limits the effectiveness of the TUT compared to the BT

Field trials would be closely monitored to maintain consistency in the data collection and statistical analysis. Specific field trial profiles would be established and conducted to obtain the appropriate statistical data.

In the single blind survey method, the TUT would be blind as to knowledge of leak locations.

It is anticipated that the BT operator and observers may have a-prior knowledge of leak locations so that TUT performance can be observed.

In the double- blind survey method, the TUT and BT and observers would be blind to where actual leaks are. Concurrent surveys would be conducted over a period of time using both TUT and BT under normal/routine surveys.

Single Survey procedure:

The following procedure can be used for the gathering of statistical performance data of the TUT.

1) The survey team will consist of two people; TUT operator and BT operator.

2) The TUT operator will be in the lead while surveying, followed immediately by the BT operator.

3) The BT operator will survey same area as the TUT scans.

4) The normal survey method for the technology should be used. Attempt should be made to survey as normal.

5) If the TUT operator misses a leak that is detected by the BT, the TUT operator will then re-scan the leak location. Note, the operator should re-scan as normal, and

then slower or at different angles/distance until detecting the gas or until determination is made that the leak is not detectable.

6) If the BT operator misses a leak that was detected by the TUT, the BT operator will then re-scan the leak location. Note, the operator should re-survey as normal, and then slow down and probe more thoroughly until detecting the gas or until determination is made that the leak is not detectable.

7) Document the leak in the leak survey database.

Double Survey procedure:

The following procedure can be used for the gathering of statistical performance data of the TUT compared to the BT. This method should be used with multiple instruments and operators to factor in the variance of use and instrument repeatability.

This survey method is intended to give a more independent measure of performance in conditions of less control relative to the single blind method. It is recognized that this testing may continue for some length of time over differing conditions, users and instruments. Consequently, the data collection may be less consistent and therefore more difficult to statistically analyze.

1) The survey team will consist of two people; TUT operator and BT operator.

2) The TUT operator will be in the lead while surveying, followed independently by the BT operator. Enough time and distance separation are required to eliminate chance that one operator may observe another, while being short enough to make sure both have the same opportunity to observe the leak.

3) The BT operator will survey same area as the TUT scans.

4) The normal survey method for the technology should be used. Attempt should be made to survey as normal.

5) Once a specified area is completed, both operators will compare leaks found.

6) If the TUT operator misses a leak that is detected by the BT, the TUT operator will then re-scan the leak location. Note, the operator should re-scan as normal, and then slower or at different angles/distance until detecting the gas or until determination is made that the leak is not detectable.

7) If the BT operator misses a leak that was detected by the TUT, the BT operator will then re-scan the leak location. Note, the operator should re-survey as normal, and then slow down and probe more thoroughly until detecting the gas or until determination is made that the leak is not detectable.

8) Document the leak in the leak survey database.

5.3 Data Quality Objectives and Monitoring, Reporting, and Recordkeeping

Regulatory agencies may have data quality objectives and monitoring, reporting, and recordkeeping requirements related to the evaluation of innovative leak detection systems. Additional information on this topic may be provided if agencies clarify the regulatory requirements.

5.3.1 Conclusion

Innovative methane detection technologies should be evaluated with a technology-neutral process that clearly defines the objectives of the system with testable metrics. Objectives can be based on concentration, emission sources, or emission reductions. Other objectives may include equivalency to other technologies and work practices – this equivalency also can be defined at the concentration, source, or reduction level. For many technologies, emission source detection limit and response time is a complex function of many parameters such as wind direction that can be determined with empirical testing and/or physics-based modeling (Figure 44). For reduction-based objectives, computer modeling can be used to predict emission reductions at the site or population level based on the technology's probability of detection and parameters related to emission mitigation work practices (Figure 45). A combination of scientifically rigorous empirical testing and modeling can fairly assess the ability of diverse technologies and approaches to meet stakeholder objectives.

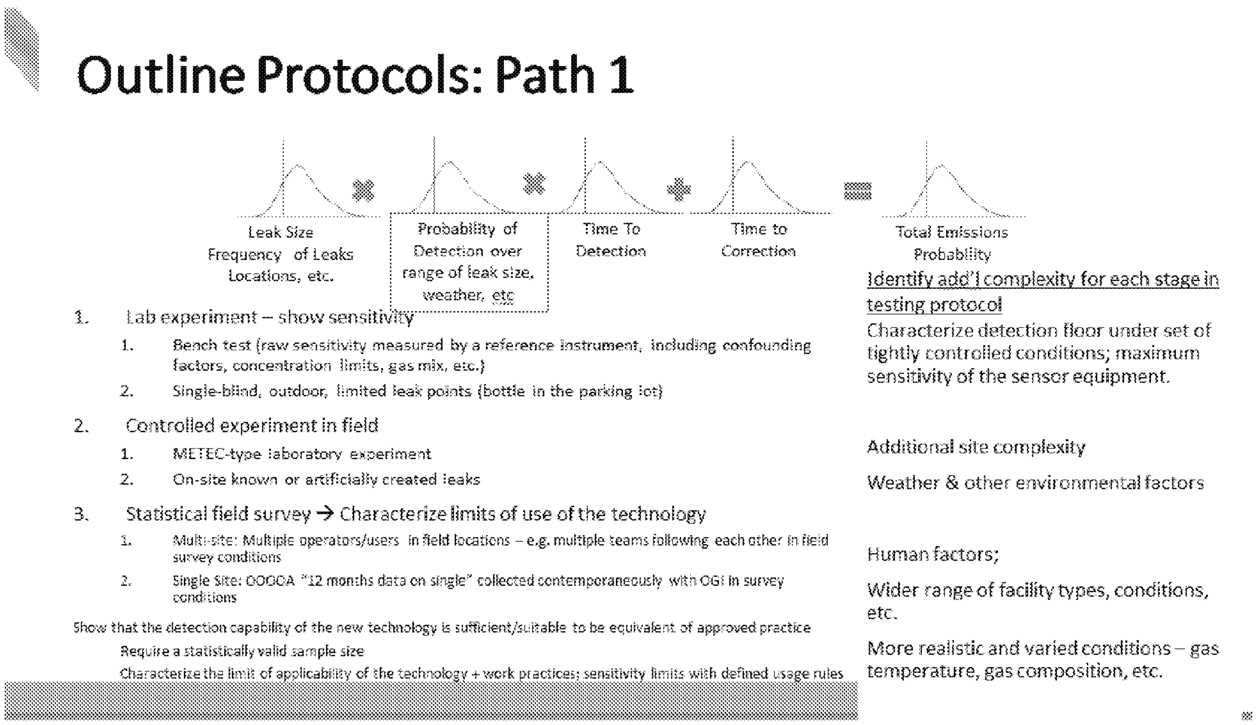

Figure [SEQ Figure * ARABIC]. A conceptual model for evaluating source-based system objectives

Source: Dan Zimmerle, Colorado State University

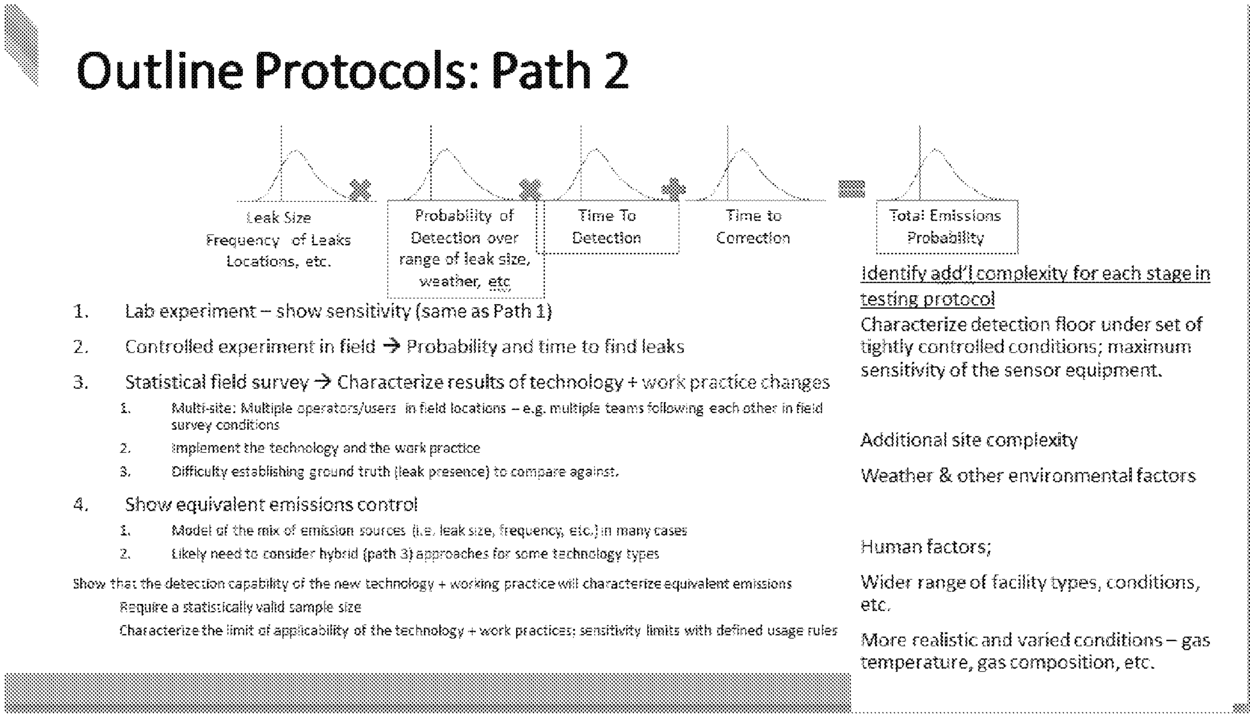

Figure [SEQ Figure * ARABIC]. A conceptual model for evaluating reduction-based system objectives

Source: Dan Zimmerle, Colorado State University

6 LESSONS LEARNED

Regulations often drive the implementation of methane leak detection programs to ensure safety and compliance. Planned and unplanned methane emissions may require different detection approaches and systems. As experience is gained in enforcing current federal and state regulations to control methane releases, shortcomings in the regulations will continue to be identified by both the regulators and the regulated industries. This is leading to development and evolving implementation of improved methane detection technologies.

Generally, methane detection technologies are moving to quantitative, continuously recorded, data-intensive systems. Cost-benefit analyses--that are required for USEPA rule-making—will require a replacement methane detection technology to be "equivalent" to an existing system. Furthermore, detection technology testing or evaluation protocols may have certain environmental limitations, which in turn may mean that a new technology is approved only for certain applications or geographical areas. There will be renewed opportunities for researchers, academics, industry, regulators, interest groups, and others to continue to improve not only the methane detection technologies themselves, but also the related regulations and the evaluation methodologies that link specific technologies to specific regulatory requirements. Including key stakeholders in the planning and implementation of the regulatory planning process is vital to the success of methane detection and control.

Partly in response to both the new technologies becoming available and to regulations increasingly requiring the adaptation of new technologies, the methodology for evaluation and selection of a methane detection technology presented in this document will need to be revised and/or expanded. This document will be updated to include these technologies as adequate information becomes available.

7 STAKEHOLDER PERSPECTIVES

This guidance has a focus on technology and detection as it relates to point sources. Stakeholders have additional concerns that pertain to the broad effects of methane and its associated toxic compounds on human health and the environment. Regulators should be aware that stakeholders may raise these concerns during discussions of the development, implementation, and compliance with regulations and technology advancement.

Environmental regulators and other parties benefit from informed, constructive stakeholder involvement because it can help them to make better decisions, reduce the likelihood of costly, time-consuming repeated work, and allow those in affected communities to properly govern the long-term use of land, water, and other resources. This section addresses the concerns of stakeholders who may be asked to participate, or comment on evaluation methodologies or specific technologies with regards to methane detection.

Identifying affected public and tribal stakeholders early in the planning process and including the key stakeholders in the planning and implementation of the regulatory planning process is vital to the success of environmental regulators decisions.

7.1 Stakeholder Concerns

This section addresses the concerns of stakeholders who may be asked to participate, or comment on evaluation methodologies or specific technologies with regards to methane detection. The ITRC broadly defines "stakeholder" as members of environmental organizations, community advocacy groups, Tribal entities or other groups that deal with environmental issues, or a concerned individual who is not a member of any organization or group. Public stakeholders, such as advocacy groups, often speak for the communities that are affected by environmental issues. In this document, a differentiation is made between public stakeholders and interested parties (oil and gas companies, pipeline operators and state regulators).

ITRC has found that environmental regulators and other parties benefit from informed, constructive stakeholder involvement because it can help them to make better decisions, and reduce the likelihood of costly, time-consuming repeated work. It also allows those in affected communities to participate in decisions regarding the long-term use of land, water, and other resources.

> ***Firestone Explosion***
>
> *On April 17, 2017, an explosion killed two people and destroyed a house in Firestone, Colorado, a community 25 miles north of Denver. An investigation conducted by the local fire department linked the explosion to an abandoned flowline connected to a gas operated by Anadarko Petroleum Corporation.*

Many public stakeholders view climate change as an existential challenge that we, as a society, must confront head on. Because methane is a potent greenhouse gas that contributes to climate change, it is likely that many stakeholders will, in general, support programs and regulations that increase the use of and improve detection of methane releases. It is often important to explain how methane contributes to environmental degradation (e.g., climate change) and safety in a reasonable, scientific way, and what can be done to reduce its impacts.

As was stated in Section 1. [HYPERLINK \l "_INTRODUCTION"], stakeholders recognize that the purpose of this document is to provide an overview of existing and developing technologies as well as guidance regarding performance characteristics and parameters to consider in technology evaluation.

> ***East Harlem Apartment Explosion***
>
> *On March 12, 2014, two adjacent five-story multi-use buildings were destroyed by a natural gas explosion and subsequent structural fire on Park Street, East Harlem, New York City. This incident resulted in eight fatalities, 48 reported injuries, and displaced more than 100 families from their homes. Information gathered during the investigation suggests that intermittent natural gas odors were detected within the incident buildings, an adjacent building, and nearby outside areas in the days preceding the incident.*

Stakeholders may have concerns if regulations or programs are limited to oil and gas production and distribution, thus requiring only a few sectors be evaluated for methane detection technology improvements. These concerns include:

7.1.1 Proximity to operating facilities with methane emissions

[HYPERLINK "https://www.aga.org/safety/pipeline-safety/federal-agency-reports-studies/national-transportation-safety-board-ntsb/nt-0"], citizens living close to operating facilities may be directly affected by methane leaks. Costly evacuations, adverse health issues, decreased property values and lifestyle disruptions are a few concerns. Stakeholders are concerned that detection techniques be evaluated that take into account where new and existing wells are located close to occupied buildings.

7.1.2 Abandoned wells and/or lines.

Abandoned wells and associated lines represent a large problem in terms of safety, land-use and release of methane. Stakeholders will be concerned if there are no requirements to check for methane leaks from abandoned wells.

7.1.3 Oil and Gas Extraction.

Stakeholders are concerned that hydraulic-fracturing ("fracking") leads to additional methane releases, especially when this process is done in areas (primarily for oil) where there is no infrastructure to collect and transport natural gas. Stakeholders may have concerns that the management of waters and muds from fracking may release methane. Detection technologies may help determine the level of methane release and additional development addressing this concern may be needed.

7.1.4 Pipeline Safety.

Stakeholders are especially concerned about pipeline safety and will like to see any program include technologies that can be used to detect pipeline emissions, especially in more urbanized areas. Stakeholders are especially concerned if the program includes technologies that are developed and evaluated that can be used to detect leaks from pipeline emissions.

The 2010 pipeline accident in a residential neighborhood in San Bruno CA resulted in the destruction of 38 homes and eight fatalities and was significant in terms of loss of life and property.

And the 2014 East Harlem gas explosion [[HYPERLINK "https://www.ntsb.gov/investigations/AccidentReports/Pages/PAR1501.aspx"] to article] resulted in the collapse of two apartment buildings, displacement of 100 families and the deaths of eight, have increased stakeholders concern about leaking distribution pipelines.

7.1.5 Adaptation of Detection Technologies.

While it is understood this document deals with oil and gas production and distribution, it may not be clear why some of the technology innovations that would be evaluated under a state program could not also be used or adapted for other types of large methane emitters, such as landfills and feedlots.

7.1.6 Oil Wells Without Infrastructure to Capture Natural Gas.

One of the largest incentives for the industry to reduce emissions of methane into the atmosphere is that the gas, if kept inside a collection system, can be sold as a product. However, there are some instances where insufficient infrastructure exists to collect that gas. In these instances, methane is usually flared or released. In North Dakota it is estimated that 30 percent of the O&G wells use flaring because of the lack of infrastructure although this percentage is dropping each year. When this condition occurs, producers may have little economic incentive, except for safety issues, to reduce methane emissions.

7.1.7 7.1.7 Underground Storage Facilities.

National attention was drawn to the large volume methane release from an underground storage system in Aliso Canyon in southern CA. Stakeholders are concerned that any program includes evaluation of technologies that will act as early detectors for these types of facilities.

7.1.8 Offshore Wells.

While it is understood by the stakeholders on this team that offshore drilling and production are outside of the scope of this document, some stakeholders may be concerned that this is overlooked, especially in coastal states. It is important to answer questions about why offshore production is excluded and if, nevertheless, some of the detection technologies can be used in an offshore setting. As noted in the Introduction, "Although off-shore emissions are of equal concern, these facilities are difficult to access (e.g., production platforms) and may be located in marine or sub-marine environments (e.g., platform-to-shore pipelines), which will require a different approach to methane emission detection." It will also be

San Bruno Pipeline Rupture

On September 9, 2010, a portion of an underground natural gas transmission system of Pacific Gas and Electric Company (PG&E) ruptured. The pipeline was located under a street intersection in a residential area of San Bruno, California. PG&E estimated that 47.6 million standard cubic feet of natural gas was released. The released natural gas ignited, resulting in a fire that destroyed 38 homes and damaged 70 more. Eight people were killed, many were injured, and many more were evacuated from the area.

Aliso Canyon Leak

On October 23rd, 2015 the largest known release of methane in US history started when a well in the Aliso Canyon Natural Gas Storage facility in Los Angeles ruptured. 8,000 residents fled the nearby Porter Ranch community due to the odor, complaints of headaches, nausea, nosebleeds, irritation of nose and throat and concern for their health. Approximately 100,000 metric tons of methane was released before the leak was plugged almost four months later. The value of the leaked natural gas is approximately $17 million, but as of the end of 2016 the total cost of the leak had mounted to $780 million to cover costs associated with the resident relocation program, efforts to stop the leak, settlements, and litigation.

important to explain who has regulatory authority for these wells.

SEE APPENDICES IN SEPARATE DOCUMENT